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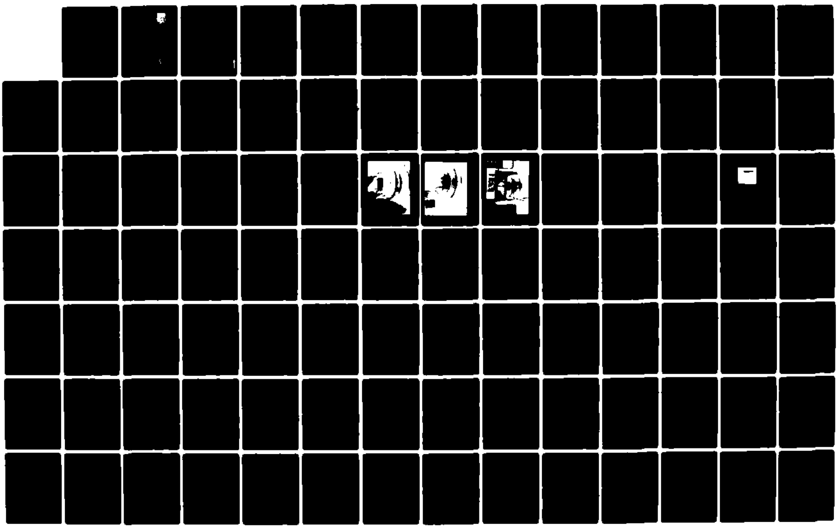

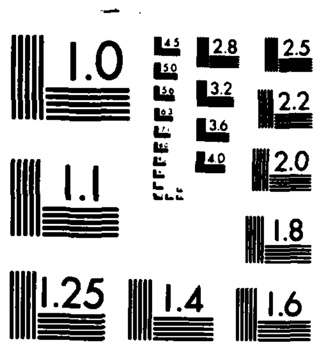

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HIGH FREQUENCY FATIGUE OF TURBINE BLADE MATERIAL

UNIVERSITY OF DAYTON
RESEARCH INSTITUTE
300 COLLEGE PARK DRIVE
DAYTON, OHIO 45469

OCTOBER 1982

FINAL REPORT FOR PERIOD OCTOBER 1979 - JULY 1982

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MATERIALS LABORATORY
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The increased fatigue crack growth rate at elevated temperature due to high frequency loading is examined. The crack growth rate is found to depend upon major cycle stress intensity factor, hold-time and minor cycle frequency, and amplitude for a given temperature. The elevated tests also demonstrate a transition from creep crack growth dominant to fatigue crack growth dominant at values of minor cycle amplitude above a threshold value. A model for determining the crack growth rate is developed.

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FOREWORD

The work described in this report was performed at the University of Dayton Research Institute and at the Metals Behavior Branch, Metals and Ceramics Division, Materials Laboratory, Air Force Wright Aeronautical Laboratories (AFWAL/MLLN), under Contract number F33615-79-C-5108. The contract was administered under the direction of AFWAL by Dr. D. I. G. Jones (MLLN). The program was conducted by the Aerospace Mechanics Group, University of Dayton Research Institute, Dayton, Ohio, with Mr. Michael L. Drake as the principal investigator.

The investigations of crack-growth behavior and modeling were conducted by Dr. Tusit Weerasooriya, Mr. Robert Dominic, Mr. Richard Goodman, and Dr. Alexander M. Brown. Generation of the data was accomplished by Miss Susan Emery and Mr. Gary E. Terborg. Data reduction and presentation, as well as software development were accomplished by Miss Elizabeth Dirkes. This work was performed during the period October 1979 to July 1982.

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SECTION 1
INTRODUCTION

1.1 INTRODUCTION TO THE HIGH CYCLE FATIGUE OF TURBINE BLADE MATERIAL PROGRAM

The high cycle fatigue of turbine blade material program was a preliminary investigation on the effect that high frequency loadings have on the fatigue behavior of gas turbine alloys. The load waveform employed was similar to that experienced by gas turbine engine components during operation; namely at elevated temperatures, a static (hold-time) load upon which a high frequency fatigue loading is superimposed. During the period of this research, this type of load waveform has become known as major/minor cycle loading.

The static hold-time with associated large amplitude unloading and reloading is the major cycle and the small amplitude, high frequency superimposed loading is the minor cycle. Figure 1.1 displays the relationship of the major and minor cycles as well as hold-time.

Interest in major/minor cycle loading has been expressed by the gas turbine engine industry because many gas turbine components are subjected to a combined loading of centrifugal and vibratory stresses at elevated temperatures similar to the major/minor cycle. The power-generating industry is also interested in the major/minor cycle approach because many components at electricity generating plants are subjected to static loads superimposed with high frequency loadings at elevated temperatures.

Of particular interest to the component designer is the amplitude of the minor cycle that has an effect on the fatigue crack propagation behavior of the major cycle. At the onset of this program, it was not known if there was a minimum minor cycle amplitude; in other words, a minor cycle threshold; below which the minor cycles have no effect on the fatigue behavior of the major cycle.

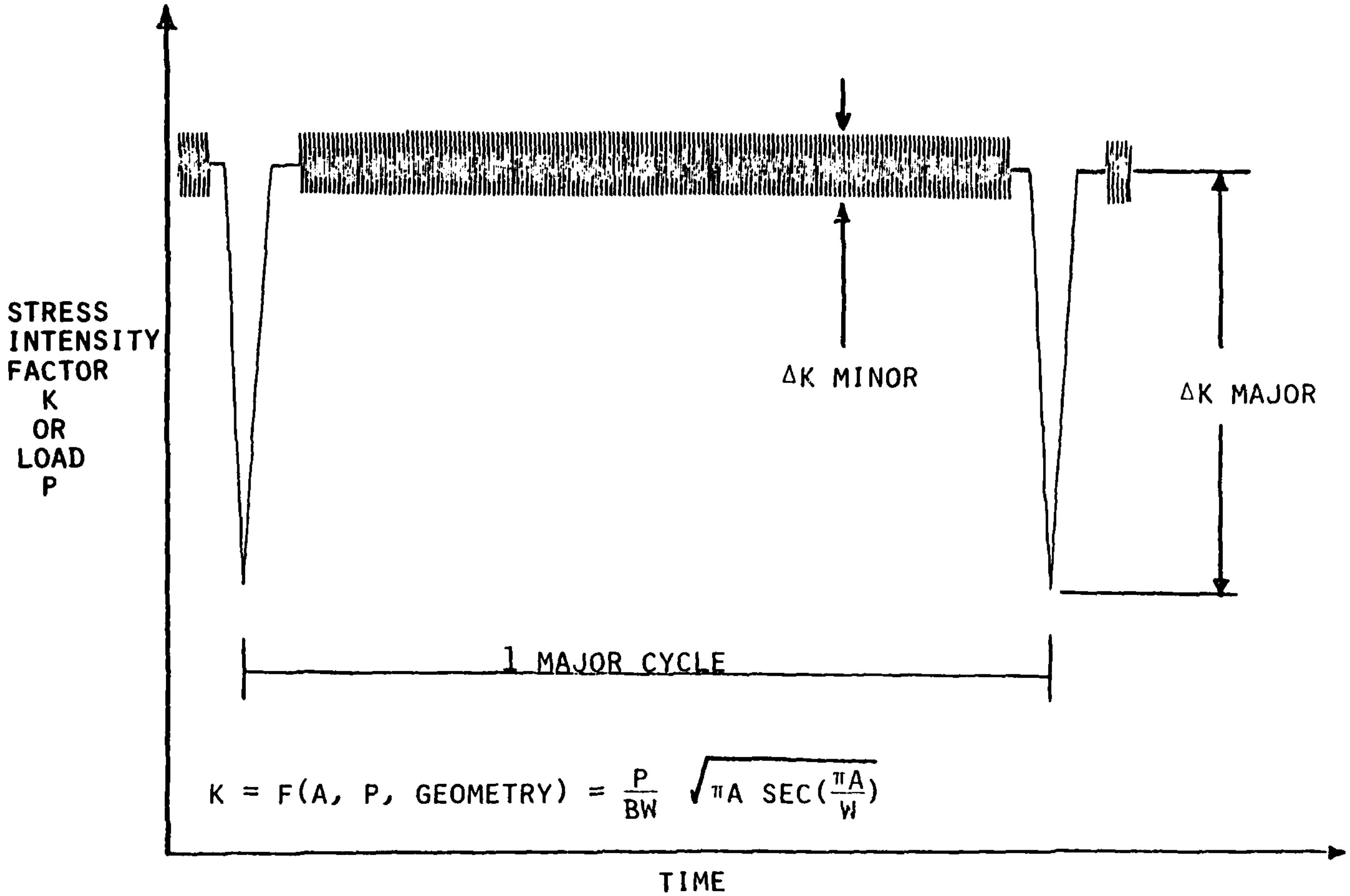

Figure 1.1. Major/Minor Cycle Load Waveform Used for the High Cycle Fatigue of Turbine Blade Material Program.

The next section (1.2) covers the nomenclature that was developed to describe the major/minor cycle program, the fracture mechanics that are associated with it, and several parameters that were developed during this investigation as part of the methodology adopted for the major/minor cycle fatigue testing.

1.2 NOMENCLATURE

1.2.1 Major Cycle (LCF)

P^{max}_{major}	[kN]	Maximum load on specimen due to major cycle.
P^{min}_{major}	[kN]	Minimum load on specimen due to major cycle, ($P^{min}_{major} \geq 0$).
ΔP_{major}	[kN]	Load range on specimen due to major cycle, ($= P^{max}_{major} - P^{min}_{major}$).
K^{max}_{major}	[MPa$\sqrt{m}$]	Maximum stress intensity factor due to major cycle.
K^{min}_{major}	[MPa$\sqrt{m}$]	Minimum stress intensity factor due to major cycle, ($K^{min}_{major} \geq 0$).
ΔK_{major}	[MPa$\sqrt{m}$]	Stress intensity factor range due to major cycle, ($= K^{max}_{major} - K^{min}_{major}$).
R_{major}		Stress ratio of major cycle, ($= P^{min}_{major}/P^{max}_{major}$).
$\frac{da}{dM}$	[mm/cycle]	Crack growth rate per major cycle.
f_{major}	[Hz]	Major cycle frequency.
HT	[s]	Major cycle hold-time at P^{max}_{major}, between unload/load action. Minor cycles are superimposed only during the hold-time of the major cycle.
M		Number of major cycles.

1.2.2 Minor Cycle (HCF)

P^{max}_{minor}	[kN]	Maximum load on specimen produced by a minor cycle superimposed onto major cycle.
P^{min}_{minor}	[kN]	Minimum load on specimen produced by a minor cycle superimposed onto major cycle.
ΔP_{minor}	[kN]	Load range on specimen due to minor cycles superimposed onto major cycle hold-time, $(= P^{max}_{minor} - P^{min}_{minor})$.
K^{max}_{minor}	[MPa$\sqrt{m}$]	Maximum stress intensity factor due to minor cycles superimposed onto major cycle hold-time.
K^{min}_{minor}	[MPa$\sqrt{m}$]	Minimum stress intensity factor due to minor cycles superimposed onto major cycle hold-time.
ΔK_{minor}	[MPa$\sqrt{m}$]	Stress intensity factor range due to minor cycles, $(K^{max}_{minor} - K^{min}_{minor})$.
R_{minor}		Stress ratio of minor cycles, $(K^{min}_{minor}/K^{max}_{minor})$.
$\frac{da}{dN}$	[mm/cycle]	Crack growth rate per minor cycle.
f_{minor}	[Hz]	Minor cycle frequency.
N		Number of minor cycles per major cycle hold-time.

1.2.3 Material and Test Parameters

T	[°C]	Test temperature.
ΔK_o	[MPa$\sqrt{m}$]	Threshold stress intensity factor range.
K_{Ic}	[MPa$\sqrt{m}$]	Critical stress intensity factor.
a	[mm]	Half crack length.
W	[mm]	Specimen width.
B	[mm]	Specimen thickness.

σ_{Lig}	[MPa]	Applied stress on unfractured ligament of specimen.
$\frac{da}{dt}$	[mm/s]	Creep crack growth rate.

1.3 GENERAL TEST CONDITIONS

It is apparent from the nomenclature in Section 1.2 that a large number of variables are required to described the major/minor cycle test conditions. The complexity of deciphering the major/minor cycle behavior of a single alloy is great, because almost all of the variables affect the fatigue behavior of the alloy.

In order to reduce the number of specimens tested during the course of this investigation to a realistic number, several of the test parameters were held constant. Most, but not all, of the tests run for this program were run under the following conditions:

Temperature = 650°C

$R_{major} = 0.1$

$f_{major} = 1.0$ Hz

$f_{minor} = 10.0$ Hz

Hold-Time = 60., 180., or 600. S

Furthermore, the material evaluated by this study was Inconel-718, a nickel-based superalloy used for components that require strength at oxidizing elevated temperatures.

In general, the procedures of ASTM standard E649 for center cracked panels were followed. Particularly, the determination of the stress intensity factor (K) as a function of applied load (P), half crack length (a), and specimen thickness (B), and width (W). It should also be noted that the normalized crack lengths (a/W) involved in this program were $0.1 \leq a/W \leq 0.4$, by and large. Section 5 deals with the effect of crack length on ligament creep stress in this region.

SECTION 2

METHODOLOGY FOR THE MAJOR/MINOR CYCLE PROGRAM

The work performed for this program was designed, in general, to conform to the current understanding of material behavior. The principal laws for this area of materials science are linear elastic fracture mechanics and the mechanisms of plastic deformation, primarily creep for this program.

The experimental work performed during the course of the major/minor program is of two types. During the early stages of the program, constant load amplitude tests were used to determine the general fatigue behavior of Inconel-718 under combined major/minor cycling. The results from these tests are covered by Appendix I. These results are valuable for determining a general crack growth rate for a range of conditions. Because the load amplitudes for both major and minor cycles were constant, the stress intensity factors, ΔK_{major} and ΔK_{minor}, increase as the crack length increases.

Although the constant load amplitude test permits a wide range of stress intensity factors to be evaluated, the tests do have drawbacks. The major/minor cycle tests are concerned with the effect of a small amplitude, high frequency loading on the fatigue crack propagation behavior of the major cycle. These tests deal with two separate stress intensity factor ranges. The first is that associated with the major cycle loading and unloading, ΔK_{major}. The second is associated with the minor cycle loading and unloading, ΔK_{minor}.

In order to simplify evaluation of the effect of the magnitude of ΔK_{minor} on the crack propagation behavior, it is necessary to hold the magnitude of ΔK_{major} constant and vary only the magnitude of ΔK_{minor}.

The evaluation of the raw data, data reduction, was carried out in as close an accordance with ASTM Standard E647 as possible.

The constant load amplitude tests were analyzed in a straightforward manner to yield the widely accepted da/dN vs ΔK plots that appear in Appendix I. The ΔK in these plots is the major cycle stress intensity factor range, ΔK_{major}. The da/dN is in fact, the crack growth rate per major cycle, da/dM, according to the nomenclature in Section 1.2.

The constant ΔK_{major} tests were evaluated and the data was plotted as da/dM, the crack growth rate per major cycle against the minor cycle stress intensity factor range, ΔK_{minor}. When the constant ΔK_{major} data is plotted in this manner, the effect of the minor cycle loading is readily apparent.

Table 2.1 is the test matrix for the constant load amplitude tests as well as the constant ΔK_{major} tests. All specimens were center cracked panels (CCT) of 0.093" thick Inconel-718 sheet with a heat treatment according to AMS 5596B. The constant load amplitude tests, (numbers 2 through 11), made use of 4" wide panels. All other tests were performed on 2" wide specimens. The crack orientation, when it was known, is cited as part of the specimen ID number in Table 2.1 using the designations, T-L* or L-T*.

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*T-L: Crack plane normal to transverse (T) disection of plate with crack front traveling in the longitudinal (L) or rolling direction; L-T: interchange the transverse and longitudinal directions in the previous statement.

TABLE 2.1

MAJOR/MINOR CYCLE TEST MATRIX FOR INCONEL 718

Test #	ID #	ΔK_{major} (MPa√m)	R_{major}	f_{major} (Hz)	Hold-Time (S)	Temp. (C)	ΔK_{minor} (MPa√m)	f_{minor} (Hz)
2	1-T-10	30-90	0.10	1.	0	650	0	0
3	5-0T-10	60-110	0.50	10.	0	650	0	0
4	1-3T-0	40-90	0.10	1.	180	650	0	0
5	1-10T-0-1	40-100	0.10	1.	600	650	0	0
6	1-3T-10	30-110	0.10	1.	180	650	6-20	10.
7	1-10T-10-1	30-100	0.10	1.	600	650	6-20	10.
8	1-10T-40	40-100	0.10	1.	600	650	8-20	40.
9	1-10T-0-2	40-110	0.10	1.	600	650	0	0
10	1-10T-10-2	30-110	0.10	1.	600	650	6-20	10.
11	82-0T-10	10-20	0.82	10.	0	650	0	0
104	81-226 L-T	27.5	0.10	1.	180	650	0-20	10.
105	81-223 L-T	33.	0.10	1.	600	650	0-4	10.
107	81-233 L-T	35.	0.10	1.	180	621	4-10	10.
108	81-221 L-T	20.	0.10	1.	180	650	5-20	10.
110	81-215 L-T	25.	0.10	1.	180	650	5-25	10.
111	81-222 L-T	40.	0.10	1.	180	650	5-20	10.
112	81-219 L-T	35.	0.10	1.	180	650	8-18	10.
113	81-251 L-T	30.	0.10	1.	180	650	9-18	10.
114	81-266 L-T	30.	0.10	1.	180	650	10-18	10.
115	81-249 L-T	25.	0.10	1.	180	650	5-12	10.
116	81-220 L-T	20.	0.10	1.	180	650	9-15	10.
117	81-224 T-L	15.	0.10	1.	180	650	12	10.
119	81-236 L-T	25.	0.10	1.	180	650	9-13	10.
120	81-195 T-L	25.	0.10	.15	600	650	2-6	200.
121	81-255 L-T	20.	0.10	1.	180	650	6-22	10.
122	81-235 L-T	25.	0.10	1.	180	650	6-30	10.
123	81-238 L-T	30.	0.10	1.	180	650	0-25	10.
124	81-200 T-L	35.	0.10	1.	180	650	7-30	10.
125	81-253 L-T	40.	0.10	1.	180	650	0-17	10.
126	82-032 L-T	15.	0.10	1.	180	650	10-30	10.
127	82-035 L-T	20.	0.10	1.	180	650	8-23	10.
128	82-039 L-T	20.	0.10	1.	180	650	7-25	10.
132	81-191 T-L	25.	0.10	.15	180	650	4-8	200.
140	82-005 L-T	25.	0.10	1.	180	650	9-20	10.
141	82-036 L-T	30.	0.10	1.	180	650	0-30	10.
142	82-046 L-T	35.	0.10	1.	180	650	0-25	10.
143	82-045 L-T	15.	0.10	1.	180	650	10-30	10.
144	82-045 L-T	15.	0.10	1.	180	650	8-10	10.
145	82-006 L-T	20.	0.10	1.	60	650	5-15	10.
146	82-009 L-T	20.	0.10	1.	60	495	5-15	10.
147	82-044 L-T	25.	0.10	1.	60	650	4-20	10.
148	82-026 L-T	30.	0.10	1.	60	650	0-20	10.
149	82-037 L-T	25.	0.10	1.	600	650	7-20	10.
150	82-004 L-T	25.	0.10	1.	600	650	0-15	10.

SECTION 3
EQUIPMENT DEVELOPMENT

3.1 MTS FRAME #4 SERVO-HYDRAULIC TEST SYSTEM

The major/minor cycle tests that had minor cycle frequencies less than or equal to 40 Hertz were accomplished using MTS Frame #4 servo-hydraulic test system. The test system is located at USAF Materials Laboratory, Wright-Patterson Air Force Base.

The system consists of the load frame with hydraulic ram and hydraulic grips, the control console, and the supply pump.

The specimens that were used during this program were center cracked panels, in accordance with ASTM Standard E647. The panels were nominally 2" wide, 15" long and 0.093" thick.

The center hole and starter notch were placed using the electric discharge spark erosion technique.

Plastic isolation pads (4) were epoxied at the ends of the specimens to electrically isolate the specimen from the test frame. Three thermocouple wire pairs were spot welded to the surface of the specimen for temperature monitoring and control.

Accessories that were added to the test frame include cooling clamps that fit the specimens. These clamps protected the hydraulic grips from overheating. A sturdy mount was fitted to the test frame for the traveling microscope used for crack length measurements.

Plastic shields were fitted to the test frame to reduce air flow and to provide protection to passers-by.

Two systems were used to heat the specimens to test temperature, typically 650°C. A Lepel induction heater was used for the majority of the tests. It provided rapid heating and an easy crack length measurement. The last few tests were run

with a resistance furnace. Both types of heating made use of a temperature controller and temperature monitor that were mounted into the control console.

The A/C electric potential technique was used to monitor the crack lengths. The technique uses an A/C current that is passed through the specimen. Pick-up wires above and below the crack are used to monitor the potential that develops due to the resistance of the metal. As the cracks grow, the potential increases. A major advantage of the A/C electric potential system is that the lock-in amplifier monitors only the desired signal, rejecting noise. Figure 3.1 shows the crack length vs electric potential data for test # 125. A polynomial was fit to the data and is shown in Figure 3.2. This polynomial was used to estimate the crack lengths from just the A/C potential output.

In order to conduct the constant ΔK_{major} tests, it was necessary to reduce the loads as the crack lengths increased. A Hewlett-Packard 2100 mini computer was used to control the test system and maintain the test parameters. Hardware that the mini computer contained were D/A converter, A/D converter, GPIB, real time clock, frequency meter, and 2 megabyte disc drive. The necessary software to run the tests under computer control was developed and proved successful.

3.2 DEVELOPMENT OF HCF/LCF TESTING CAPABILITIES

3.2.1 Background Rational of Instron HCF/LCF Testing Machine Purchase

In early 1980, discussions were held with ISI-Ling and with MTS regarding performance and prices of hydraulic testing machines capable of performing combined HCF/LCF testing. These machines were capable of achieving 100 to 180 Hz for HCF testing of our proposed Inconel 718 center cracked panel test specimen, which at that time was to be 4.0 inches wide and 0.093 inches thick. These frequencies could be achieved with

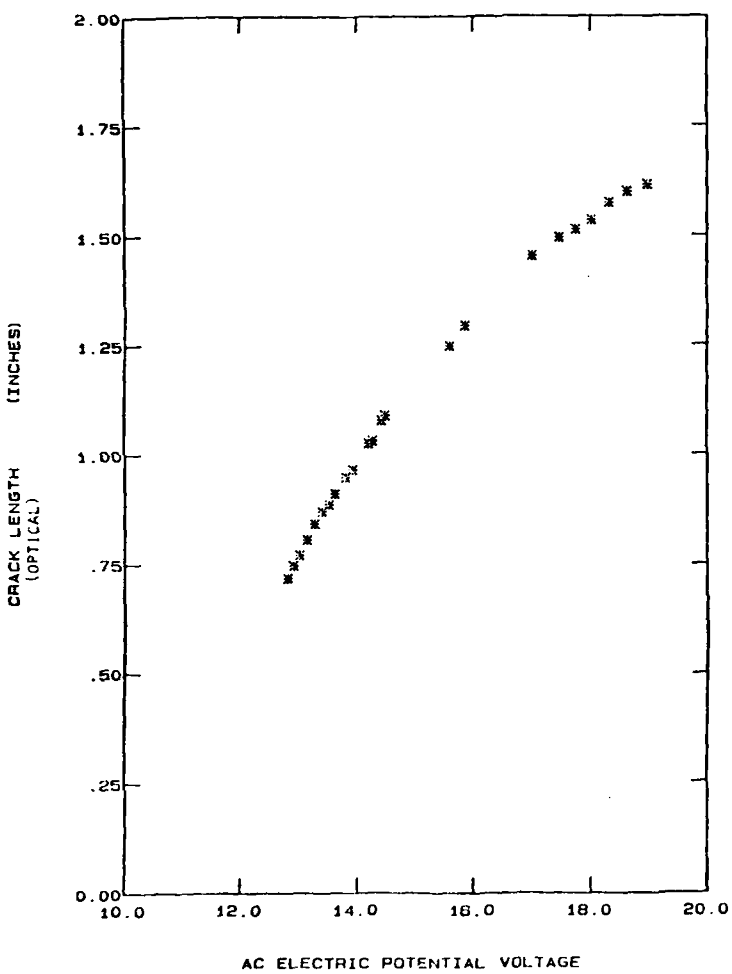

Figure 3.1. AC Electric Potential Data for Test # 125 (ΔK_{major} = 40 MPa$\sqrt{m}$). The Output Voltage is Plotted Against the Optically Measured Crack Length.

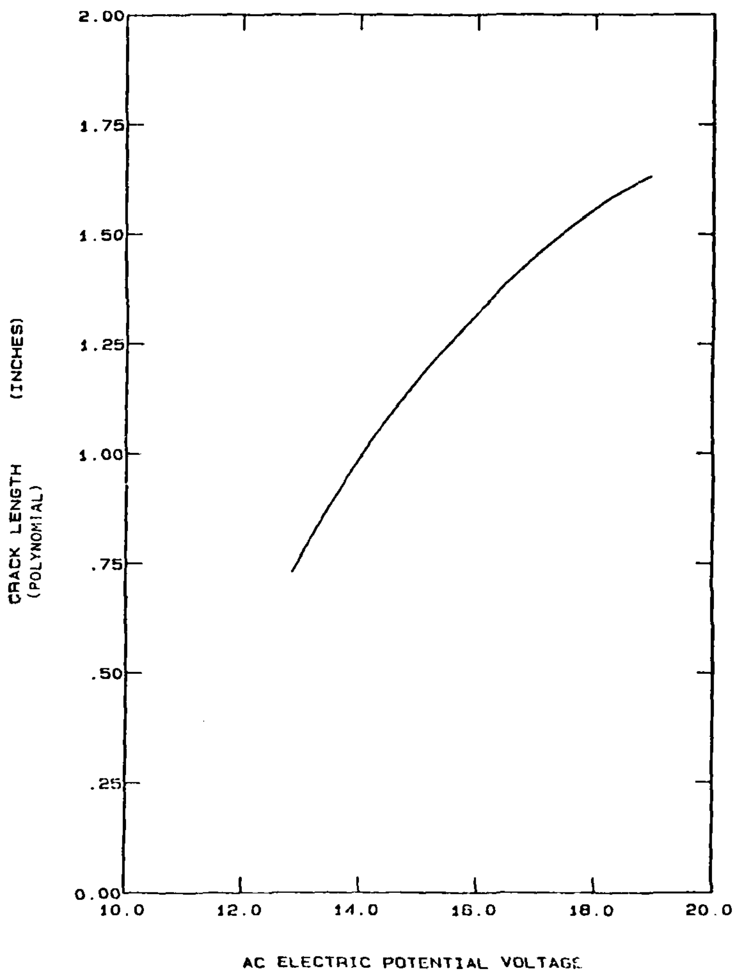

Figure 3.2. Best Fit Polynomial (4th Degree) of AC Electric Potential Data From Test # 125.

a 10.0 kilo pound alternating load superimposed on an LCF load of up to 20.0 kips. Firm price quotes were received for these two test machines.

Either of these two test machines would have required a substantial and fairly expensive hydraulic power supply of 90 gpm flow rate at 3,000 psi. There was a possibility of acquiring a surplus power supply of 250 gpm capacity from AFWAL/FDL. However, that power supply was extremely large and required 4160 volt, 3-phase power for the drive motor. The required high voltage power would have been expensive to install at Building 32, and installing such a large and noisy system in the laboratory was not at all desirable.

In addition to several discussions concerning these two test systems, two meetings were held with Instron Corporation personnel in May 1980. Instron had recently developed a test machine based on an electrodynamic shaker system for HCF loads superimposed on a hydraulic or worm-gear-imposed LCF load. This machine had about twice the frequency range of the hydraulic machines and required only a 2.0 gpm hydraulic power supply, or none at all if gear-driven. However, it had only a ±2.0 kip capacity for the HCF load cycles and was more expensive than the hydraulic machines. It would have required rethinking the concepts planned for the program as to specimen heating and crack length measurements. A meeting between UDRI and AFWAL/MLLN was held on 10 June 1980 to discuss the advisability of the use of the lower load-capacity machine. To facilitate discussion, Table 3.1 was prepared for this meeting to illustrate the load requirements for various center crack panel geometries (different width and thickness) when the stress intensity factor conditions were the same for the starting crack length.

TABLE 3.1

LOAD REQUIRED TO ACHIEVE SAME STRESS INTENSITY FACTOR (K) AT DEFINED CRACK LENGTHS FOR DIFFERENT WIDTHS AND THICKNESS CCT GEOMETRIES

Ratio of Crack Length to Width $\frac{a}{W}$	Width W (inch)	Half Crack Length a (inch)	Thickness B (inch)	Mean Stress Intensity Factor K_m ($ksi\sqrt{in}$)	Mean Load Required P_m (kips)	Range In SIF ΔK ($ksi\sqrt{in}$)	Load Amplitude P_a (kips)
0.075	4	0.30	0.093	26.1	10.0	5.2	±1.0
0.075	4	0.30	0.020	26.1	2.2	5.2	±0.2
0.075	2	0.15	0.093	26.1	7.0	5.2	±0.7
0.075	2	0.15	0.050	26.1	3.8	5.2	±0.4
0.075	2	0.15	0.020	26.1	1.5	5.2	±0.2

It was decided at this meeting to get new cost quotes from ISI-Ling, MTS, and Instron based on a 2.0 inch wide x 10.0 inch long specimen subjected to a maximum ±.010 inch static strain with maximum ±.003 dynamic strain superimposed. The objective was to achieve higher frequency dynamic loading of at least several hundred Hertz. The quotes were received in July with ISI-Ling indicating 180 Hz, MTS indicating 300 Hz, and Instron indicating 600 Hz as maximum achievable dynamic loading. The quoted prices were $77,000 for the ISI-Ling system, $133,000 for the MTS system, and $139,000 for the Instron system. Based on these performance and cost values, and also on the required hydraulic power supply sizing, UDRI recommended to the government that the quoted Instron system be purchased.

3.2.2 Installation of the Instron HCF/LCF Testing Machine

The Instron "Major/Minor Cycling System", serial number M0121, was received at Wright-Patterson Air Force Base in March 1982, and installed in rooms 300 and 327 of Building 32.

The system consists of the following:

- Instron model 1334 load frame rated at ±250 kN equipped with a 50 kN hydraulic actuator.
- Instron model 1506 electromagnetic shaker.
- Instron model 1536 power amplifier capable of 8 kW output.
- Instron field supply.
- Instron cooling unit (water-recirculating/heat exchanger type).
- Electronics for generation, level control, and monitoring of major/minor signals.

AFWAL supplied the hydraulic pump package, an MTS 6 gpm unit to which the Instron had been wired to interface. Operation of the system was acceptably demonstrated by Instron personnel in May 1982.

Elevated working platforms were fabricated for ease of reaching the specimen area. A traveling microscope was mounted to the load frame. An induction heating coil and water cooling pads were also installed. Grips were fabricated to accomodate our Inconel crack growth specimens and to allow electrical isolation for a future potential measuring system.

3.2.3 In House Development of Electromagnetic Shaker HCF/LCF Testing Machine

In the Spring of 1980, UDRI was evaluating available fatigue testing equipment that might provide potential approaches for obtaining the fatigue life of turbine blade materials under high frequency loading and to evaluate all approaches and the currently available equipment at AFML for their ability to conduct high frequency fatigue tests, and to recommend a course of action which would lead to the appropriate testing capability. From this effort, a technique was conceived at UDRI for HCF/LCF testing by hydraulically coupling an electromagnetic shaker to a standard MTS machine. An experiment was designed to determine the feasibility of this technique. The test showed such a technique would be useful to an HCF frequency of 120 Hz and to higher frequencies with additional developmental effort. The brief experimental program is described and the results are presented in UDRI-TM-80-28, "Experimental Coupling of Electrodynamic Shaker to MTS Cylinder," which is included as Appendix III of this report. This shaker-hydraulic approach was abandoned for one of more promising potential - direct axial installation of a shaker in the load train with some suitable coupling to the high force low cycle load source.

Several concepts were considered before development of the currently operational system. The configuration in Figure 3.3 would have utilized a shaker mounted on a standard tension testing machine. The LCF load would have been applied through the concentric shaft which was to have high compliance. The configuration of Figure 3.4 was then offered as one requiring no modification of the shaker, and the air cylinders were to provide the compliant coupling of LCF load to specimen, i.e., coupling the more steady state LCF load without restriction to the shaker armature, allowing the shaker energy to be utilized in the specimen. After calculations of the air cylinder dimensions for the desired compliance, another configuration, Figure 3.5, was conceived by UDRI. This concept used the shaker head itself as the air cylinder piston which minimized the mass to be driven at high frequency as well as made available a "piston" of the required diameter to achieve high compliance. Finally, Figure 3.6, it was decided to eliminate the tension loading machine and to apply the LCF loading by controlled pressure to the chamber. In April 1981, developmental effort began for a testing apparatus of this configuration (Figure 3.6). An MB model C10 shaker was available with a load frame built for it for the hydraulic coupling experiment. The pneumatic pressure chamber was fabricated in the AF zone shop. The pressure chamber diameter was selected to be 9.7 inches in diameter and 2.0 inches deep. A pressure of 68 PSIG is then required to achieve a 5.0 Kip LCF load. At a pressure of 68 PSIG, the pneumatic stiffness is only 3,000 lb/in, according to the relation

$$k = \frac{\gamma P A}{L}$$

where

k = stiffness

γ = 1.4 for air

P = pressure

A = area of piston

L = length of cylinder

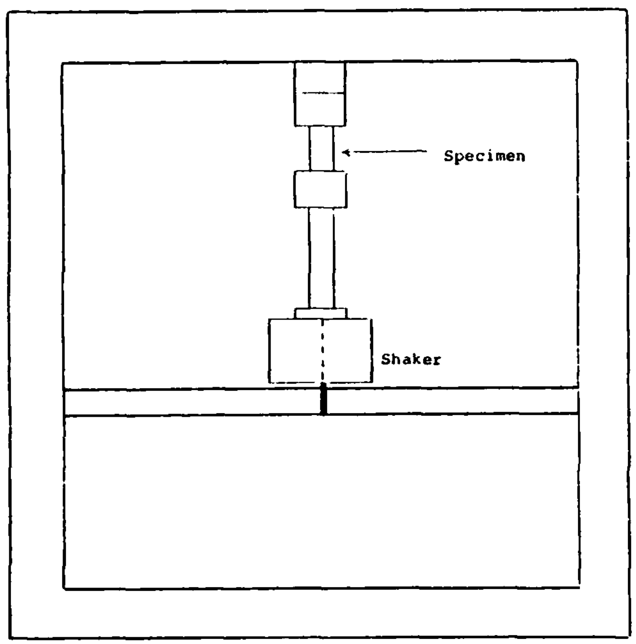

Figure 3.3. Shaker Mounted With LCF Load Applied Through Concentric Shaft.

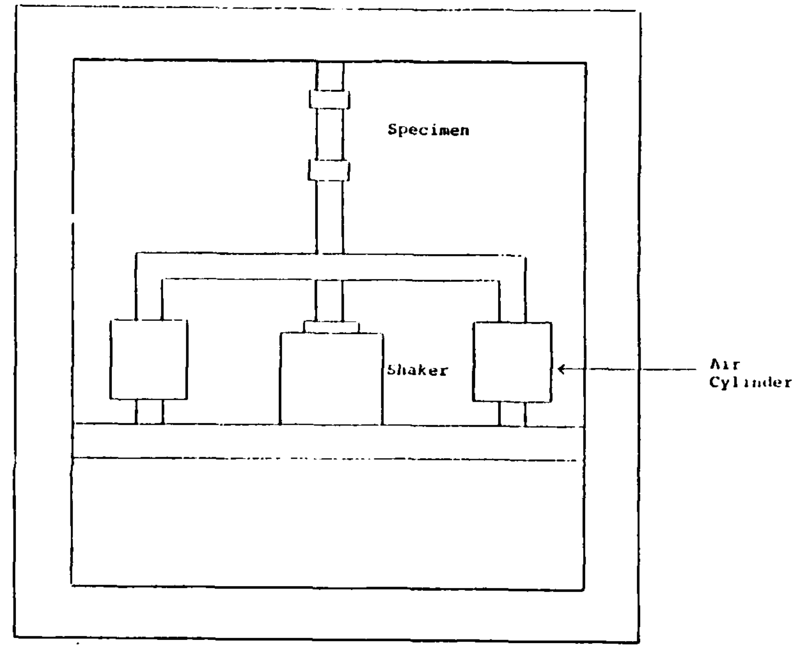

Figure 3.4. Shaker Mounted With Air Cylinders Providing The Compliant Coupling of LCF Load to Specimen.

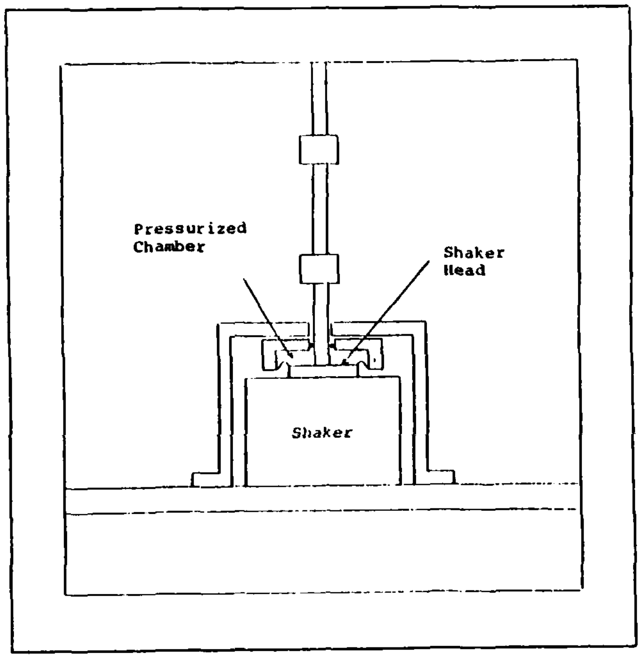

Figure 3.5. Shaker Head Utilized as Air Cylinder Piston and also Utilized as "Piston" to Achieve High Compliance.

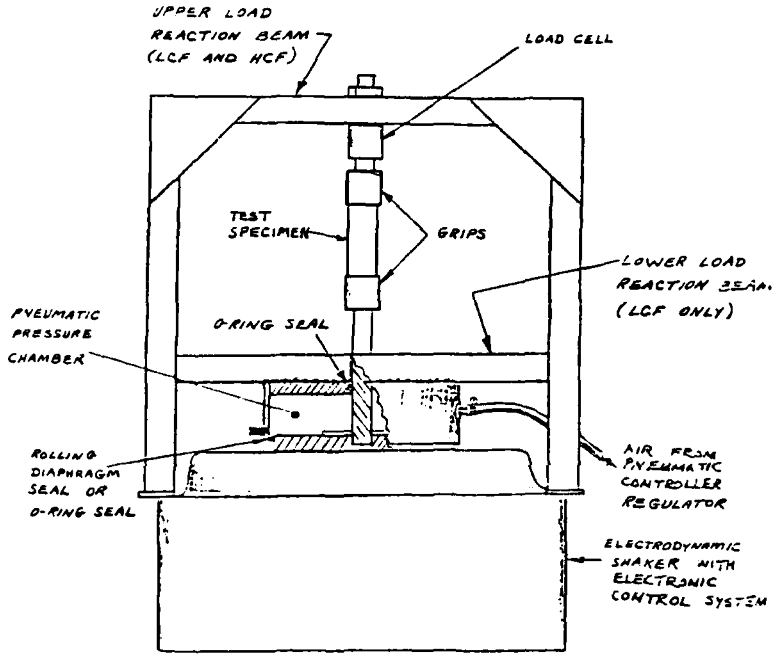

Figure 3.6. LCF/HCF Load System Schematic.

Since the pneumatic stiffness is small compared to that of the specimen, the shaker energy is mostly dissapated in the specimen. Application of the low cycle load deflects the shaker head only a few mils which its one inch range of travel absorbs easily.

A major design objective for this shaker-based HCF/LCF test apparatus was to maximize the high frequency capability. This objective necessitated minimizing the mass that was dynamically excited. Before special grips were designed and fabricated of titantium, an intermediate experiment was decided upon. In place of grips and specimen, a simple load shaft of comparable stiffness was fabricated. The load shaft was strain gaged, calibrated in tension, and fitted in the apparatus for the first test of the shaker-pnuematic test machine. Results of the intermediate experiment (12 May 1981) using the load shaft are included here in Table 3.2. After the promising performance of the load shaft experiment, it was decided to continue the development of a test machine of the configuration in Figure 3.6.

Fabrication of titanium alloy grips (Ti-6Al-4V) was completed in early June 1981. The apparatus assembly is shown in Figures 3.7 through 3.9.

Weights of the components in the dynamic load train were as follows:

C-10E Shaker Armature (original equipment)	18.00 pounds
Head reinforcement disc (titanium)	2.96
Lower grip	0.28
Upper grip	0.27
Bolts	0.40
Test specimen (Inconel 7.5x2.0x0.096 inches)	0.42
TOTAL WEIGHT	22.33 pounds

TABLE 3.2

AIR CHAMBER/SHAKER LCF/HCF TEST RESULTS OF 5/12/81
PRELIMINARY RESULTS

1000# Tension Preload		2000# Tension Preload	
Frequency (Hz)	Dynamic Load Attained (# pk to pk)	Frequency (Hz)	Dynamic Load Attained (# pk to pk)
300	500	300	500
500	500	500	500
585	500	587	500
700	500	700	500
900	210	900	distorted waveform
1,020	480	1,020	470
1,496	220	1,511	250
1,834	125	1,846	160
2,983	300	2,000	160
5,001	150	2,883	300
		4,998	150

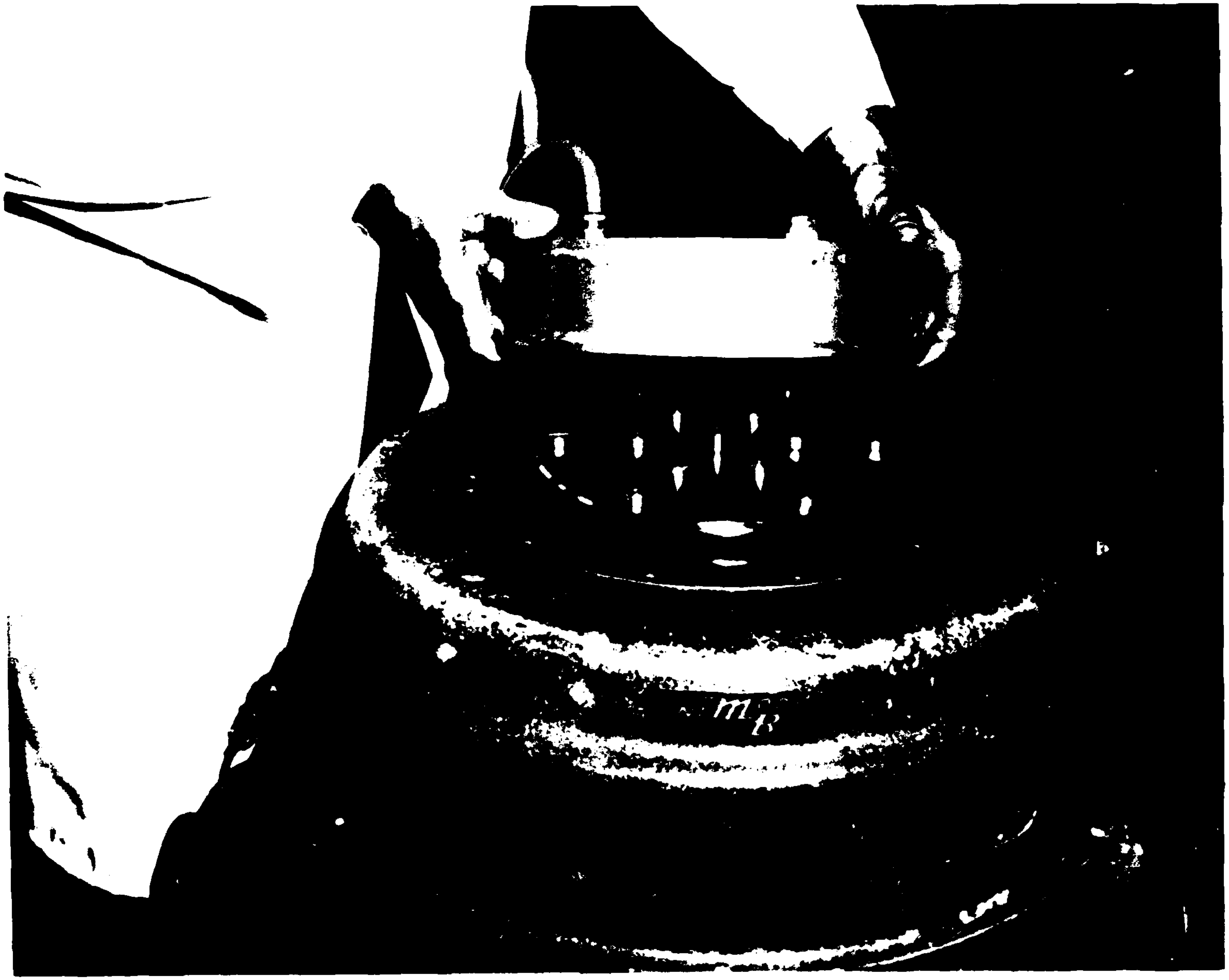

Figure 3.7. Placement of Pressure Chamber on Shaker Head, with Titanium Reinforcement.

Figure 3.8. Pressure Chamber in Place.

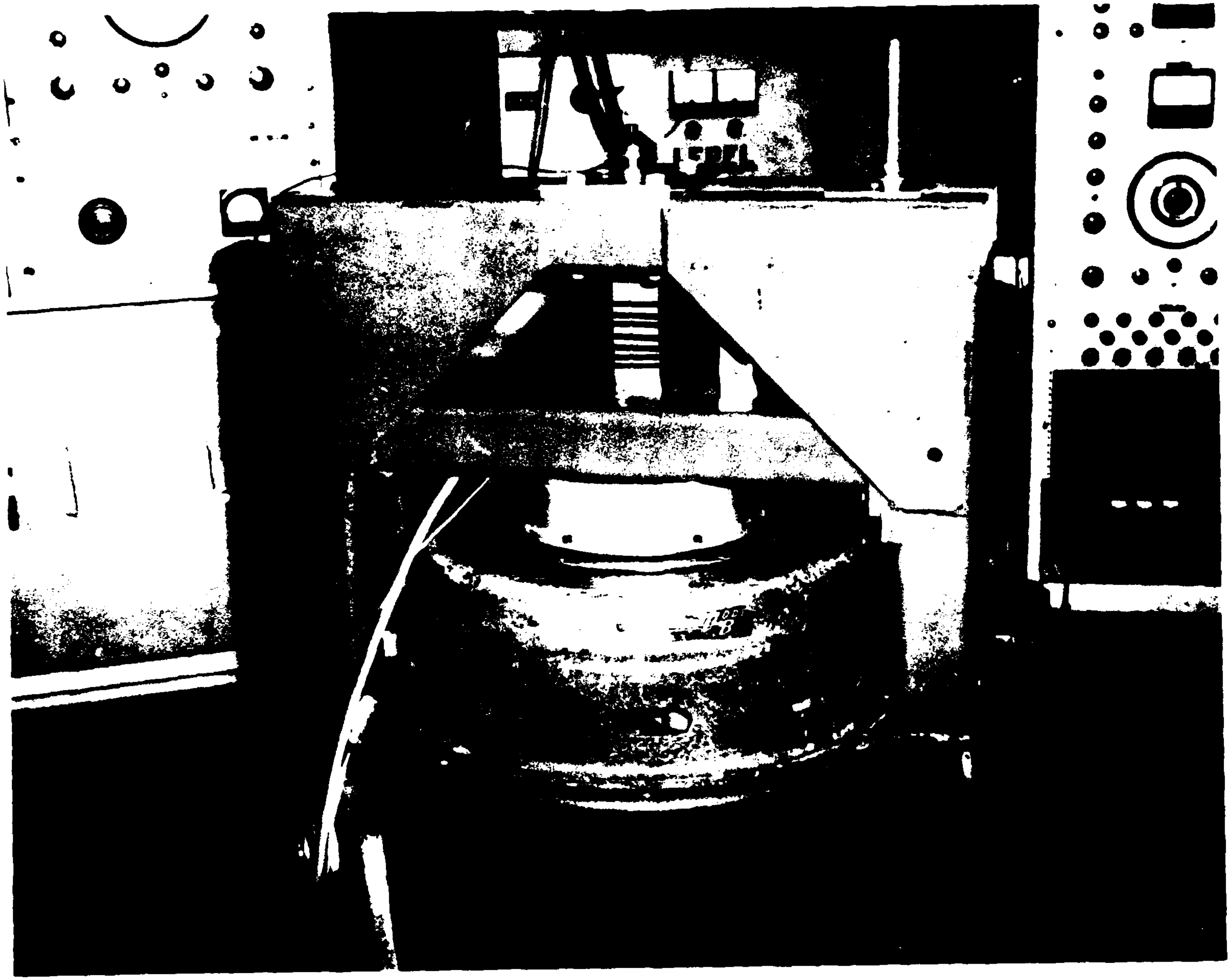

Figure 3.9. HCF/LCF Fatigue Machine Installed on Shaker with Induction Heating Coils.

3.2.4 Performance of the First Shaker-Pneumatic Test Machine

Approximate maximum available dynamic loading from the C-10 shaker was calculated by dividing the shaker force by the total accelerated mass (tabulated on page 19) as follows:

$$\text{Maximum acceleration available} = \frac{1{,}200 \text{ lb force peak}}{22.33 \text{ lb}} = 54 \text{ g}$$

At 1,000 Hz, 54 g corresponds to 0.0011 inch deflection. The system static stiffness was measured at 4.5×10^5 lb/in (details of this measurement are given later in this section). Thus, 0.0011 inch deflection would result in a specimen load of

$$(0.0011 \text{ inch})\ (4.5 \times 10^5 \text{ lb/in}) = 500 \text{ pounds (peak-to-peak)}$$

Calculated estimates of maximum available dynamic load for other frequencies were plotted along with actual maximum dynamic values (obtained by operating at maximum allowable shaker power) in Figure 3.10.

To evaluate specimen bending under dynamic excitation, low mass accelerometers were bonded to the specimen at various locations to measure lateral acceleration and one to the lower grip to measure vertical (longitudinal) acceleration. A degree of bending was indicated. The third bending mode of the specimen was determined to be 2,670 Hz with 1,500 pounds preload. Improved grip alignment is expected to reduce the non-resonant bending.

Load control and measuring of the number 1 shaker-pneumatic test apparatus is illustrated in Figure 3.11. A UDRI-designed pneumatic control unit was operational in August 1981. Utilizing simple components, an electronic timer, differential pressure switches, and precision regulation, it cycles the major (LCF) load and slaves the minor (HCF) control electronics. The original pneumatic control had a slow ramp time as illustrated by Figure 3.12. More attention to this parameter in the No. 2 machine design should result in a 0.1 second response time.

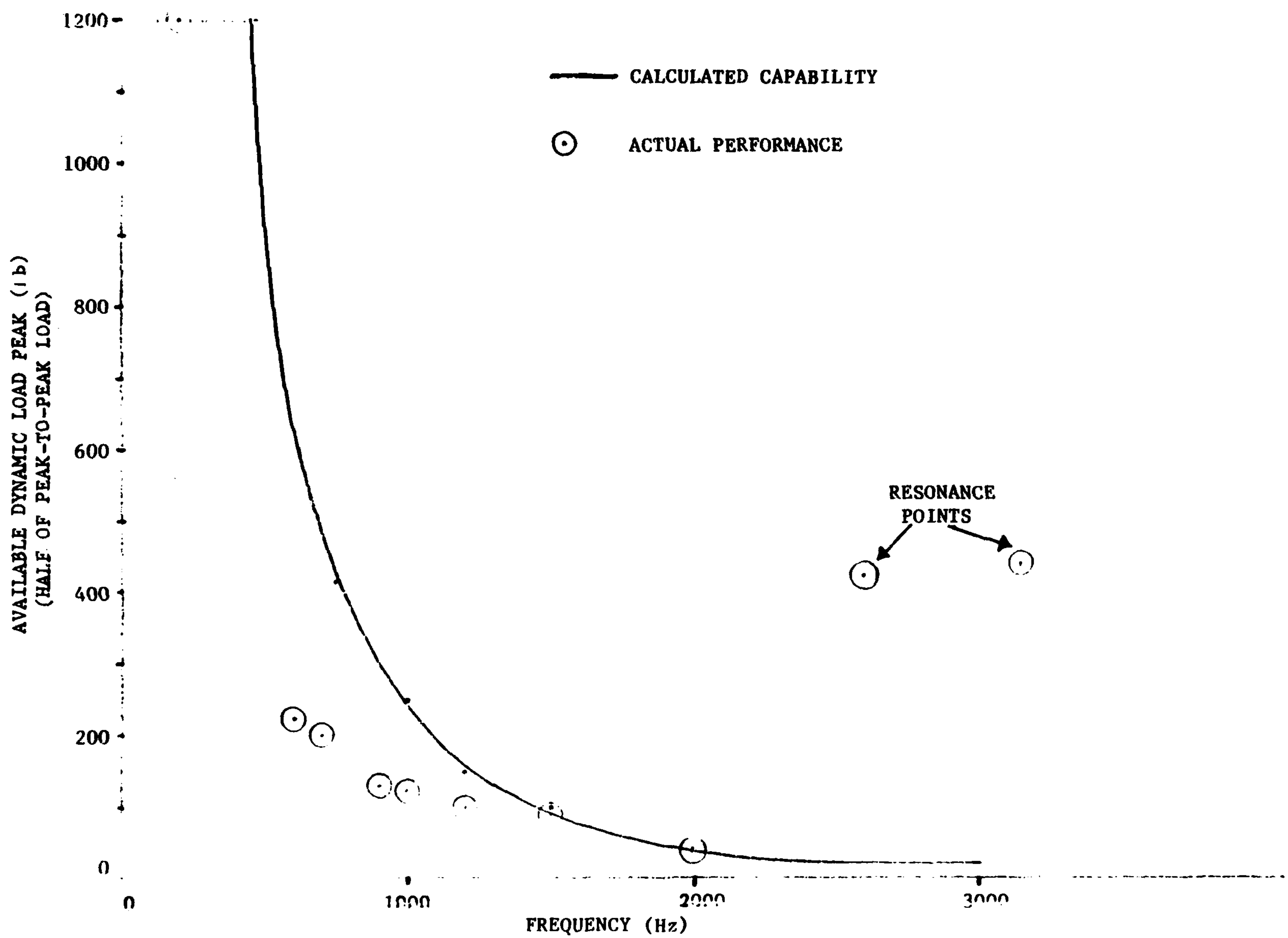

Figure 3.10. High Frequency Load Capability of First Shaker Pneumatic Testing Machine Fitted with Inconel Center Cracked Specimen .093 x 2 x 7.5 Inches.

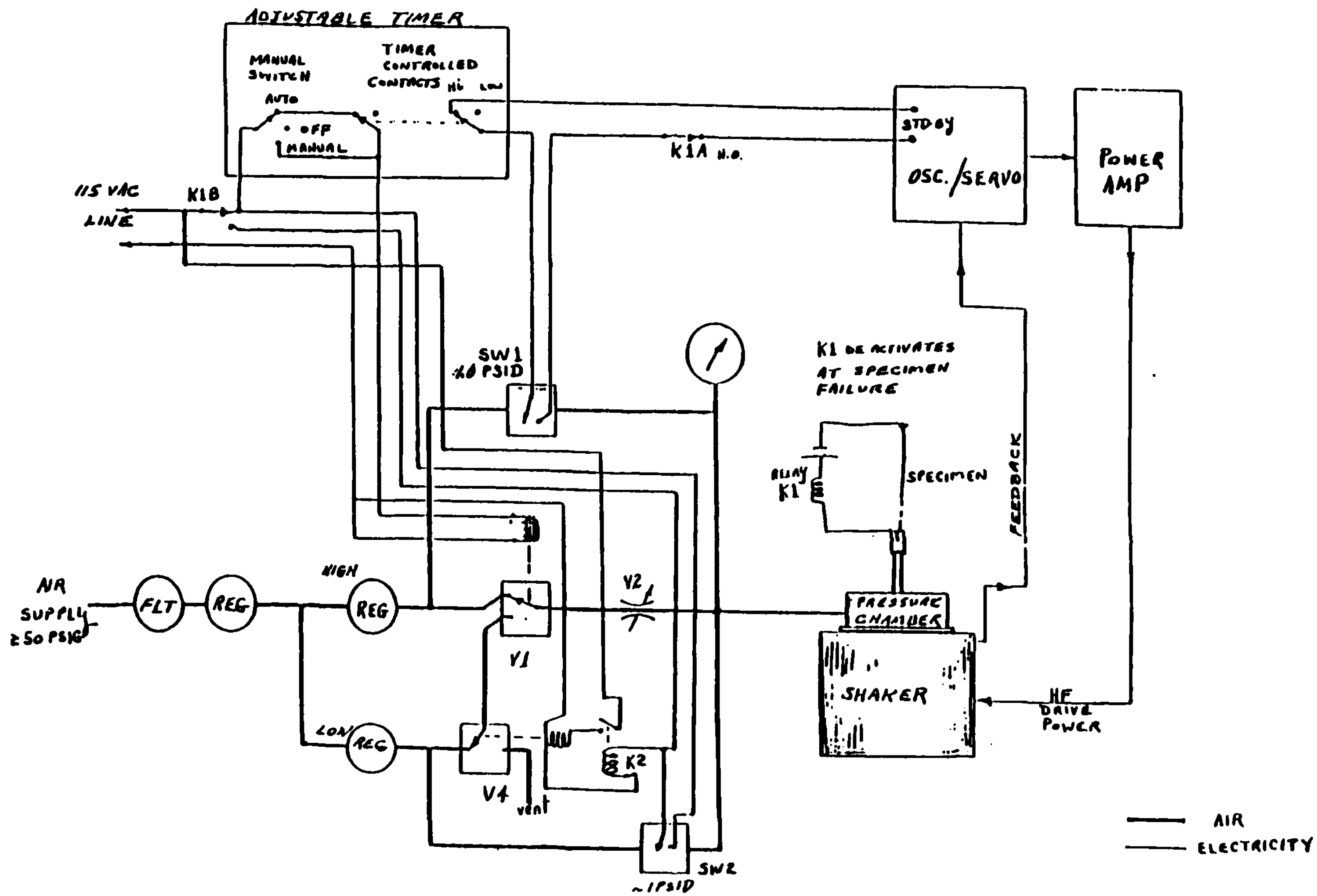

Figure 3.11. Shaker/Pneumatic Fatigue Apparatus HCF/LCF Control.

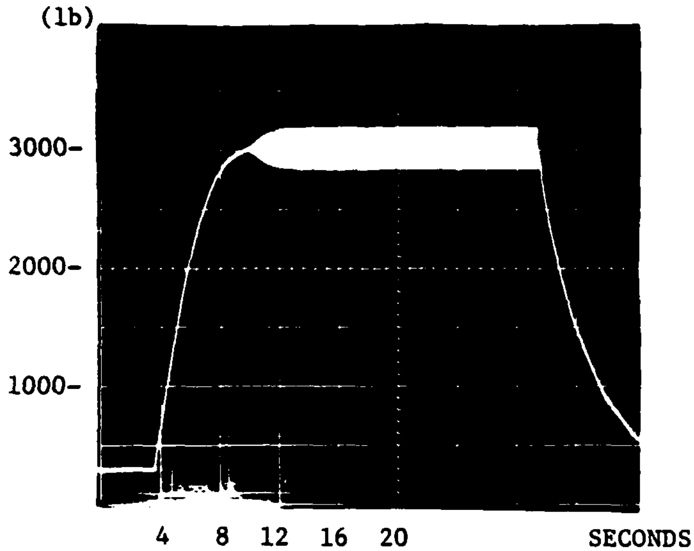

Figure 3.12. Illustration of Slow Ramp Time.

The lower grip on the No. 1 machine was fitted with four strain gages and this "integral load cell" was calibrated. Also, a quartz force gage was utilized, above the specimen, which was more immune to the induction heater.

A static compliance test was conducted on the load frame 1 July 1981. A dial indicator provided load frame deflection readings while static loads were applied by the air chamber. Results of the compliance test were as follows:

Load Pounds	Deflection Inches
0	0
1,000	0.0022
2,000	0.0045
3,000	0.0069
3,500	0.0080

In the operating range of 3,000 to 3,500 pounds, the frame stiffness is then 4.5×10^5 lb/in.

The first crack growth rate test on the No. 1 shaker-pneumatic test machine was completed in September 1981. This test, No. 102, was done with the same parameters as for a previous test accomplished on an MTS machine (UDR-TR-81-53, page B-8, test 9). The results agreed well. Test T132, also accomplished on the No. 1 machine, yielded data which agreed with that derived by a second MTS machine. Maximum loads applied during a third test were 2,000 lb peak-to-peak at 200 Hz superimposed on 4,300 lb static.

The No. 1 machine experienced a failure when the aluminum bolts which held the reinforcing ring to the shaker head failed. The aluminum bolts have been replaced with graded steel bolts. There was not damage to the C10 shaker, but the lower shaft/grip was bent and required replacement.

3.2.5 Second Generation Shaker Pneumatic Test Machine (SPTM)

A second SPTM was built in the Spring of 1982. This No. 2 machine consists of a stiffer 20 Kip load frame fitted to a higher "g" rated C20 shaker. A more sophisticated computer commandable pneumatic load controller has been designed and partially completed for this second machine.

The load frame, Figure 3.13, is capable of 20 Kip tension loads and the new load chamber is capable of 300 psig pressure necessary for 20 Kip load. However, a crucial pneumatic control component, the I/P transducer, is available with only a 150 psig rating, and thus the LC load capacity will be 10 Kip. The use of the I/P (current-to-pressure) transducer for controlling the air chamber pressure will allow complex load waveforms and computer control as illustrated in Figure 3.14. The diameter of the air chamber was kept about the same (9.875 inch) as this gives an optimum area - good pneumatic control resolution and reasonably low operating air pressures.

An innovative method of low cycle load measurement is also planned for the No. 2 machine. The air chamber pressure will be measured electronically and load calculated as a function of pressure. Remotely located and pneumatically coupled, the sensor will be immune to induction heater noise. Also, the electronic pressure readout is very accurate (±.1% of full scale total error).

The C20 shaker has a lighter armature and a higher force rating. Estimated dynamic load capability vs frequency of the No. 2 machine is shown in Figure 3.15.

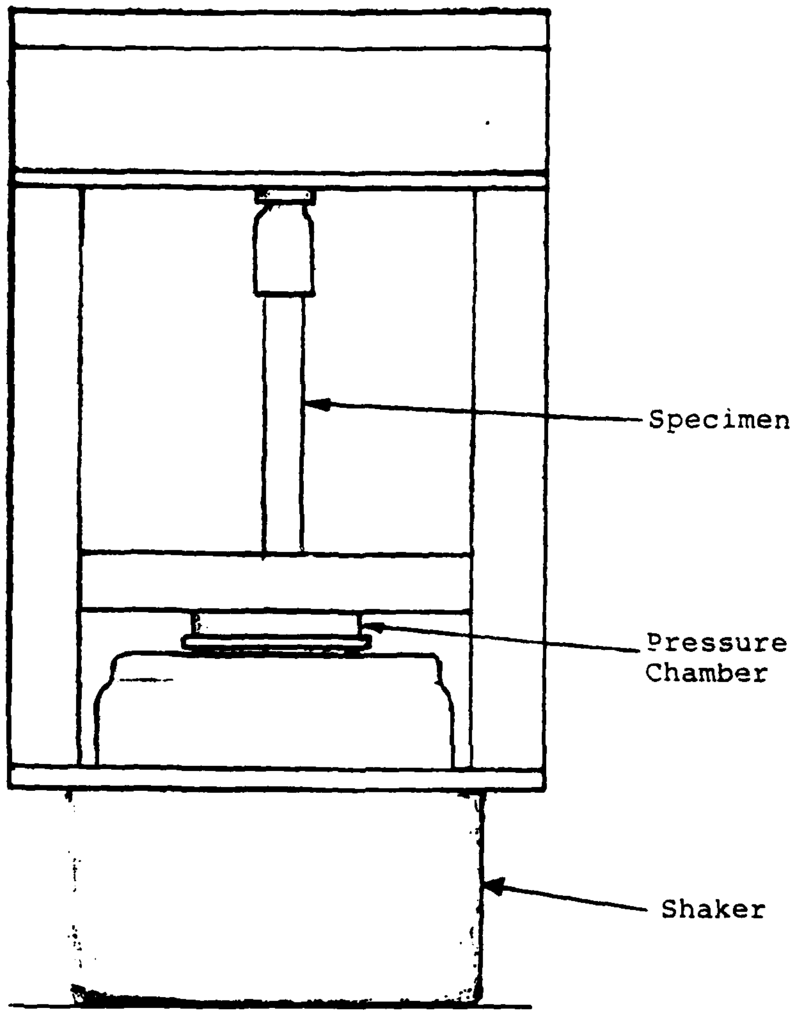

Figure 3.13. HCF/LCF Test Machine C20 Shaker, UDRI Load Frame 20,000 lb LCF Capability.

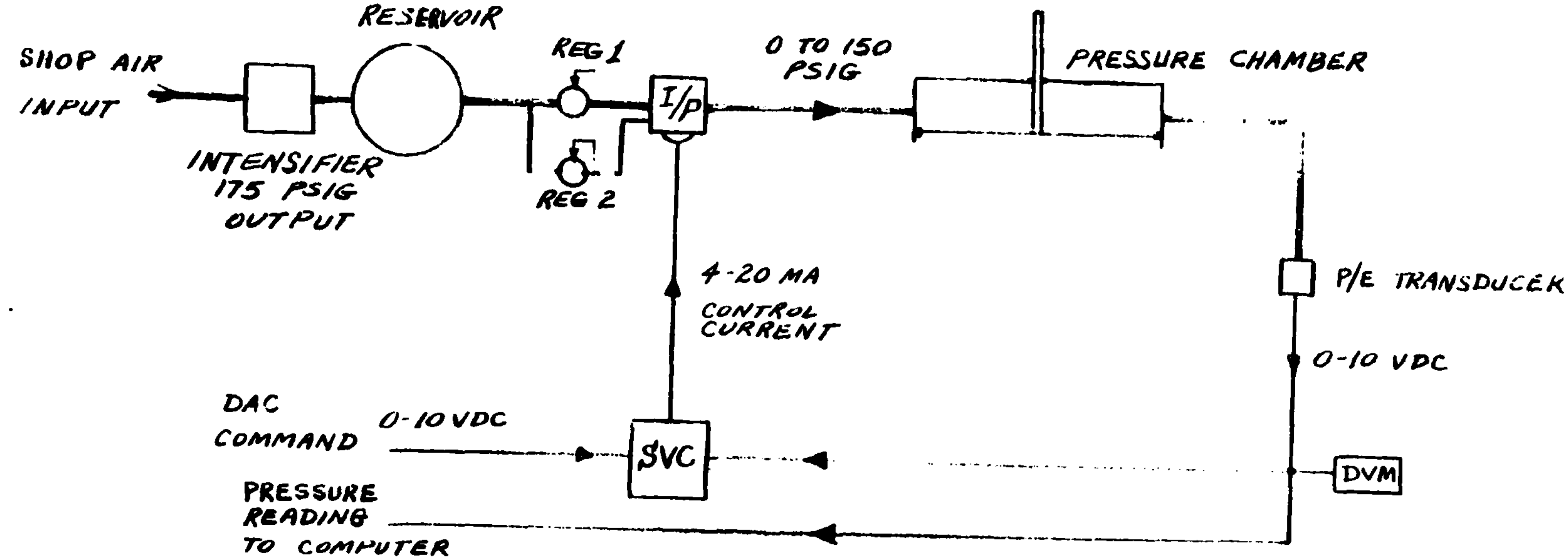

Figure 3.14. Schematic of Major/Minor Cycle Control System.

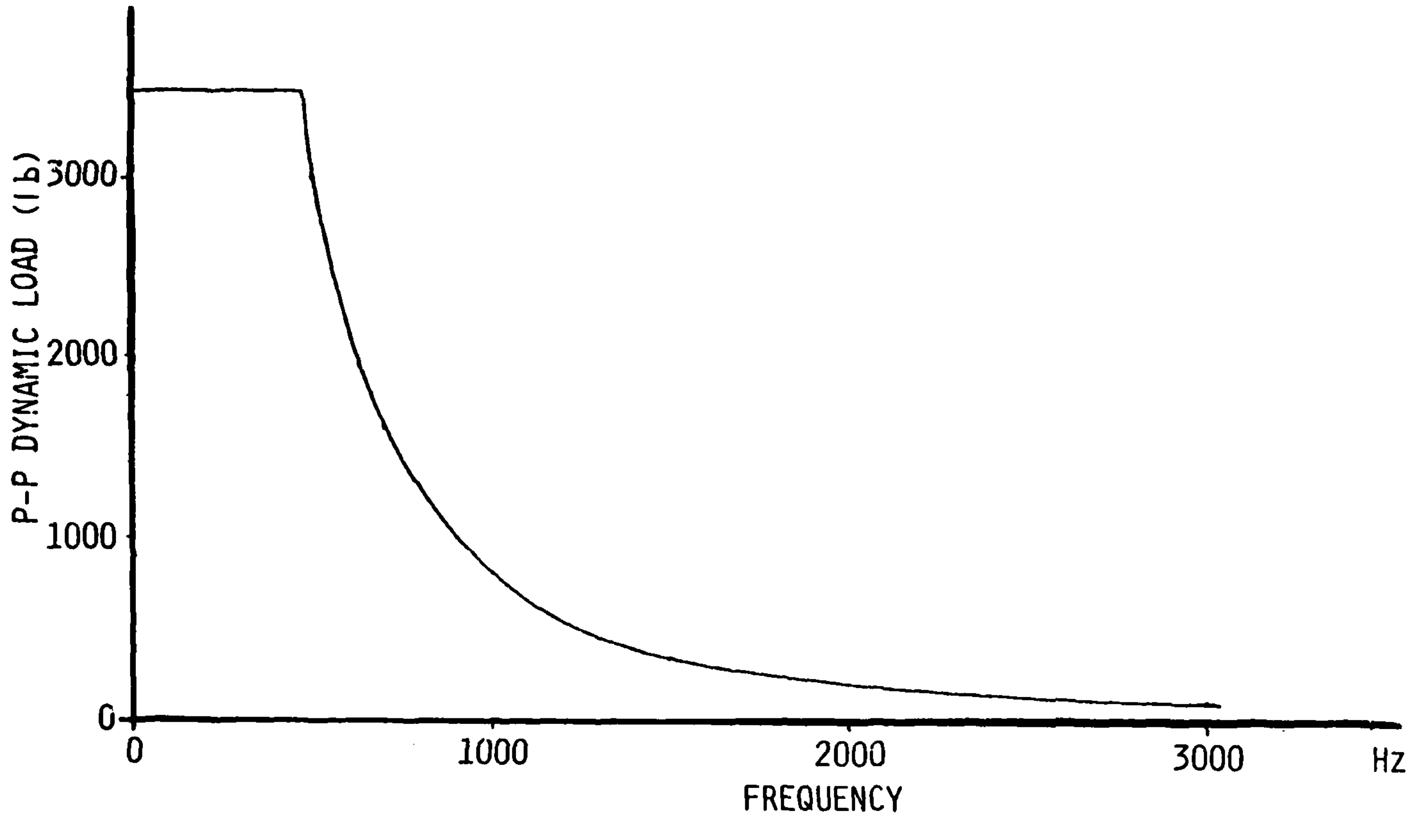

Figure 3.15. Estimated High Frequency Capability of New HCF/LCF Test Machine with Inconel Specimen .09 x 2 x 8 Inches.

SECTION 4

CONSTANT ΔK_{MAJOR} TEST RESULTS

This section contains the test results for test numbers 104 through 150. These tests were run under computer control in such a manner that ΔK_{major} was constant throughout the test. The data is presented as da/dM vs ΔK_{minor} plots and in tabular form. The plots show the relationship of crack growth rate per major cycle to the minor cycle stress intensity factor range. The actual test conditions are fully described in the test matrix, (Table 2.1), in Section 2.

The reduction of the raw data from the constant ΔK_{major} tests was done on the USAF CDC computer.

The data plotted was checked to ensure that the ΔK_{major} was within a given error bound, typically 2 MPa$\sqrt{m}$, and that the general conditions of ASTM Standard E647 were maintained.

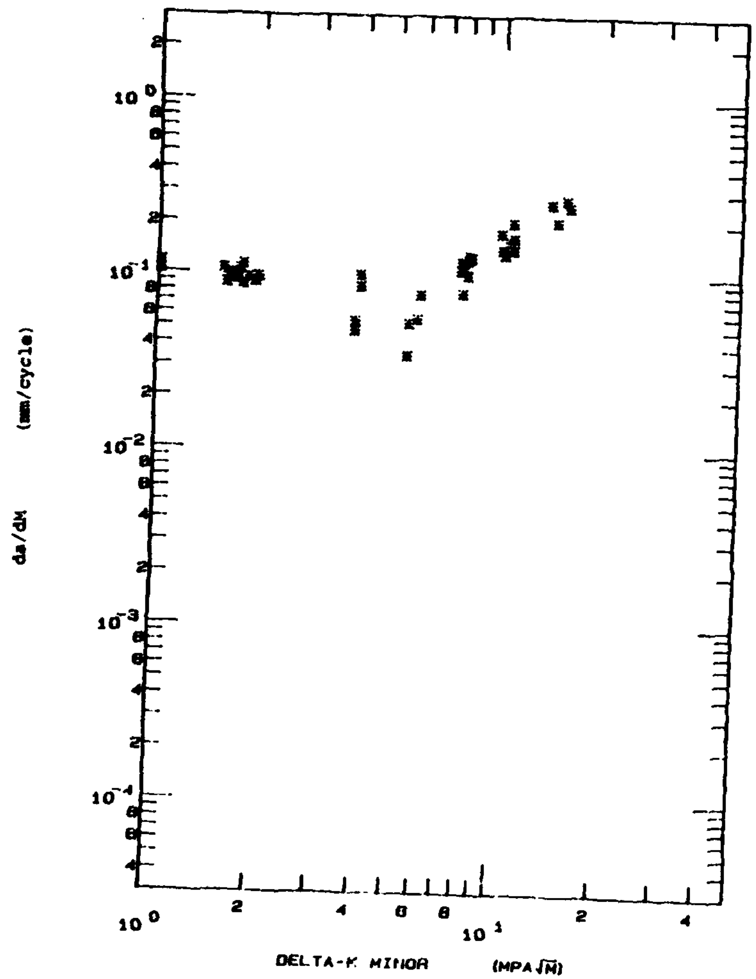

Figure 4.1. Test #104, Delta K Major = 27.5.

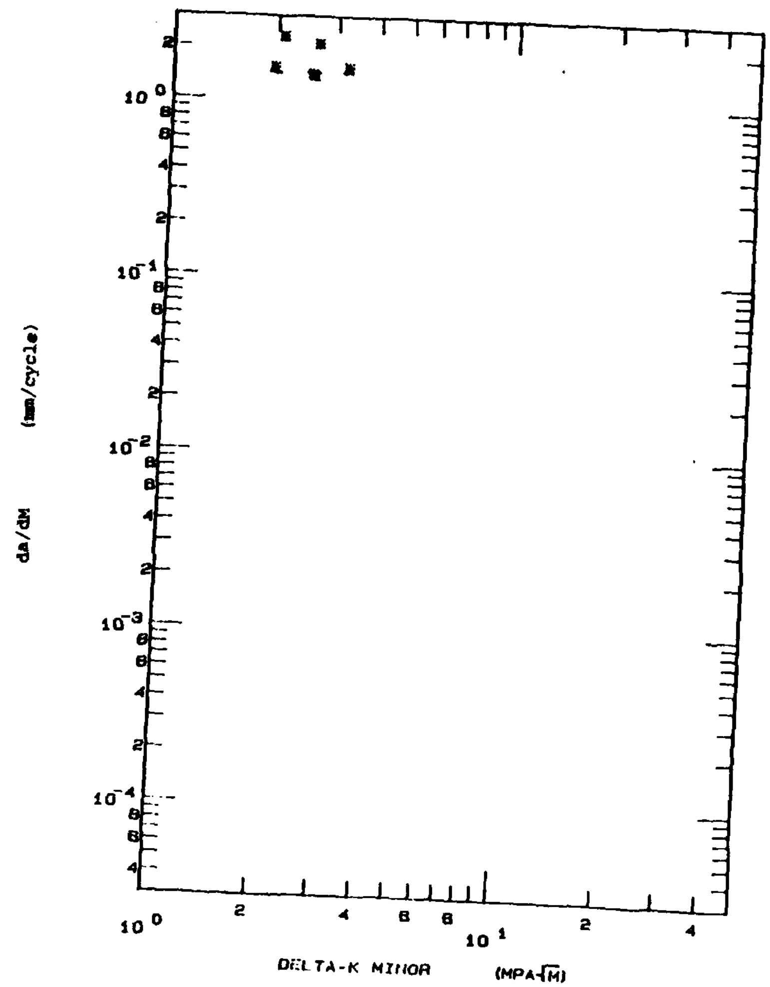

Figure 4.2. Test #105, Delta K Major = 33.0.

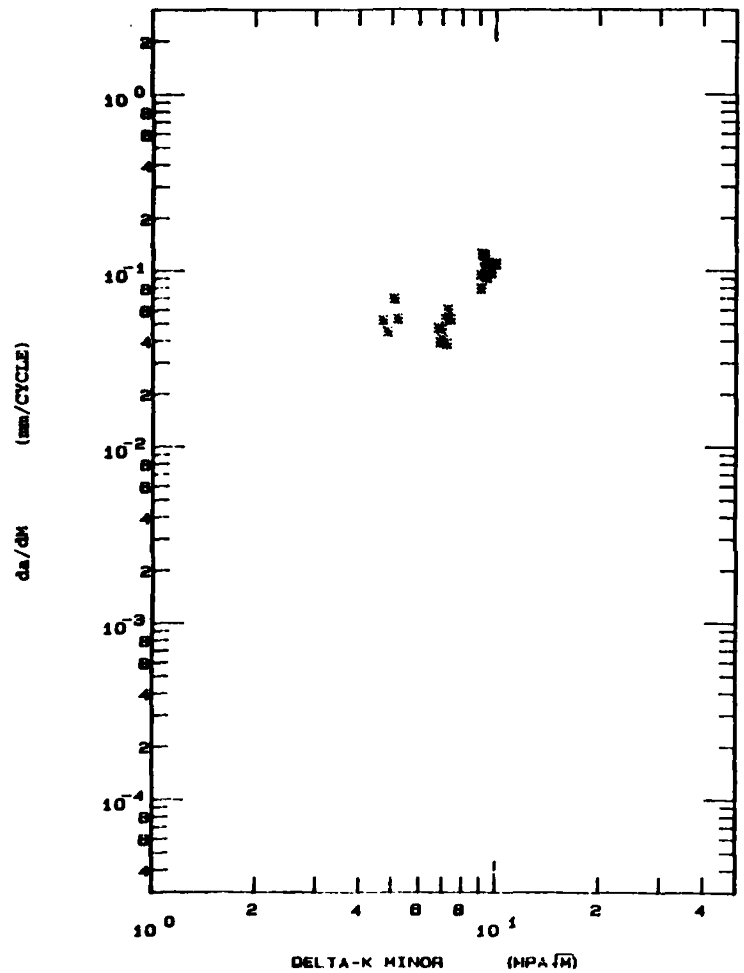

Figure 4.3. Test #107, Delta K Major = 35.0.

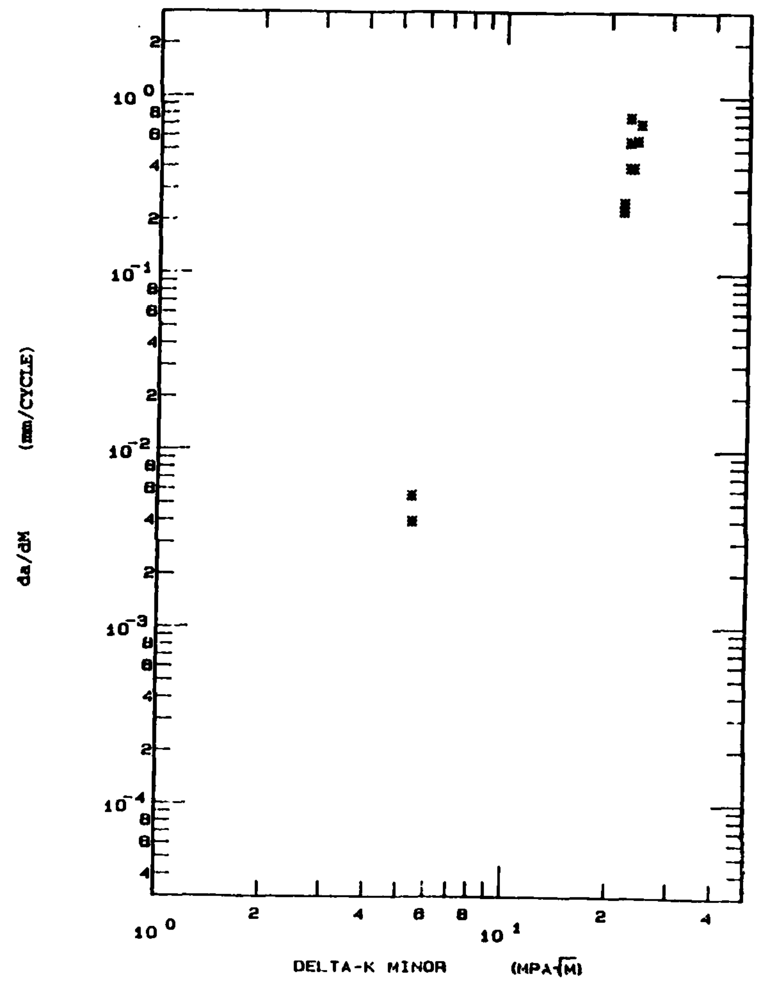

Figure 4.4. Test #110, Delta K Major = 25.0.

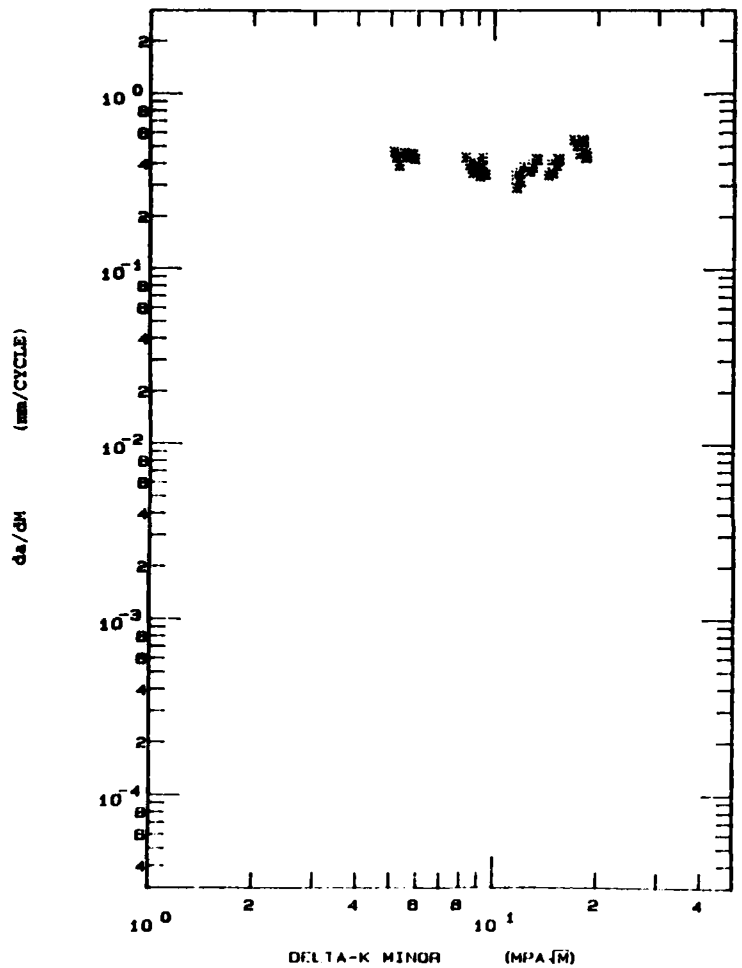

Figure 4.5. Test #111, Delta K Major = 40.0.

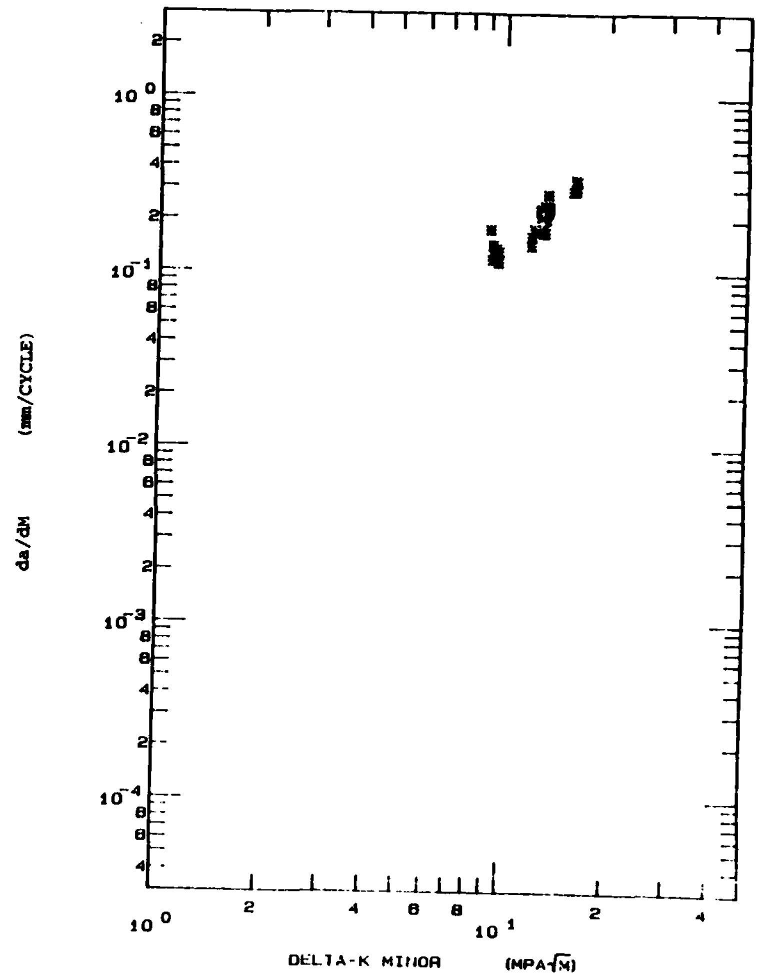

Figure 4.6. Test #112, Delta K Major = 35.0.

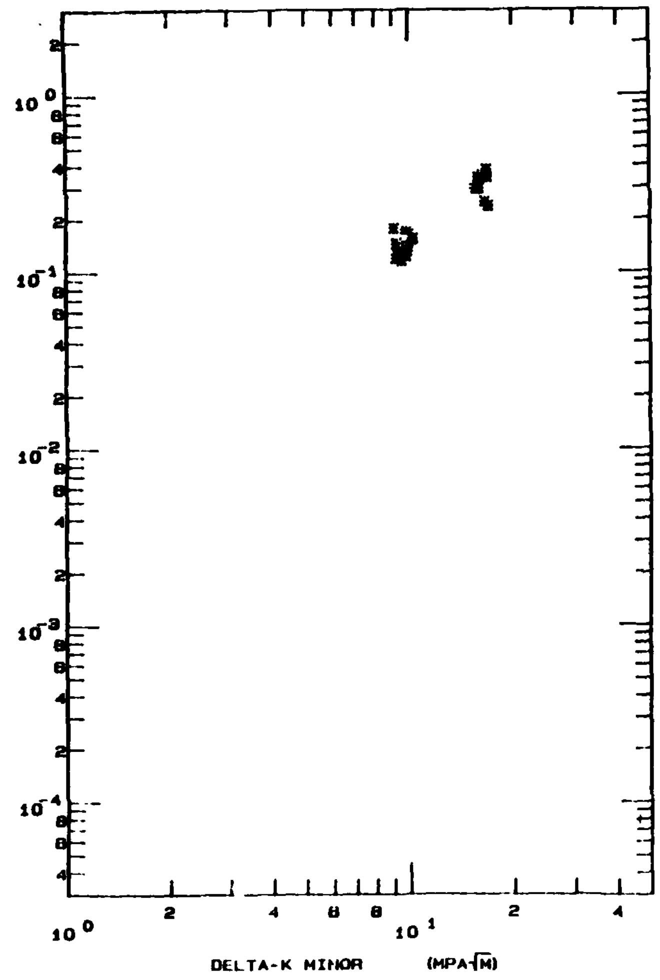

Figure 4.7. Test #113, Delta K Major = 30.0.

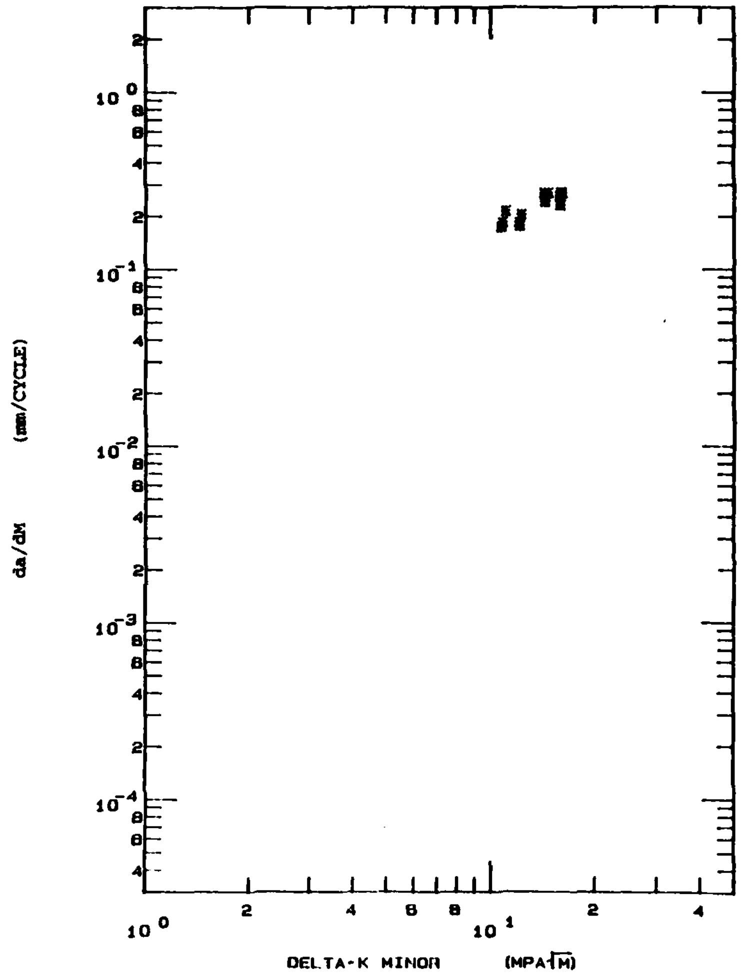

Figure 4.8. Test #114, Delta K Major = 30,0.

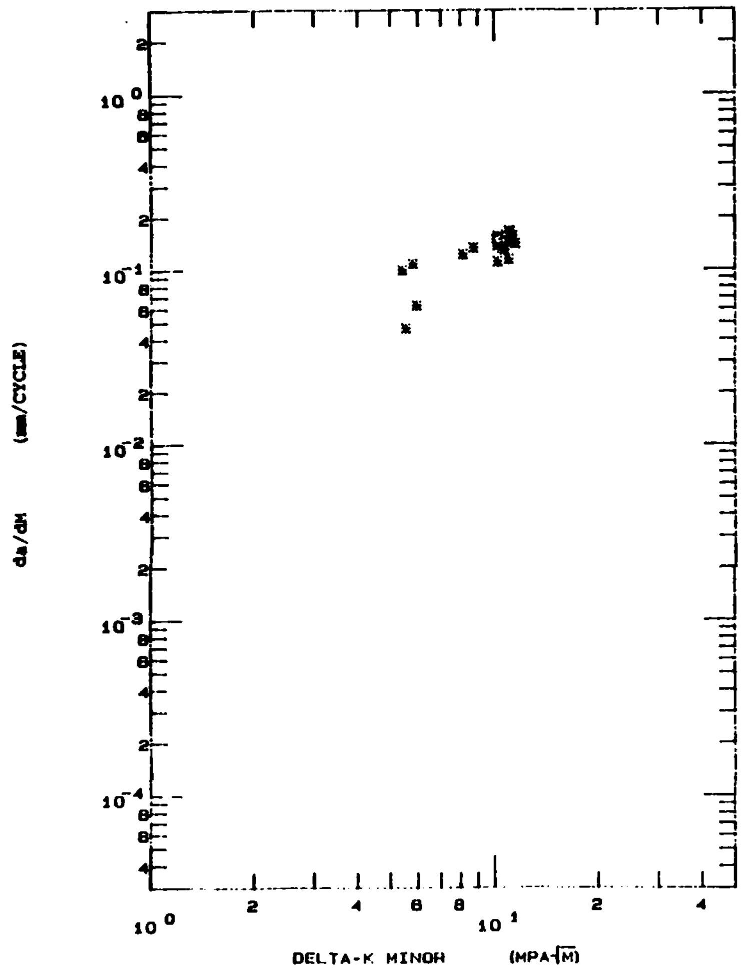

Figure 4.9. Test #115, Delta K Major = 25.0.

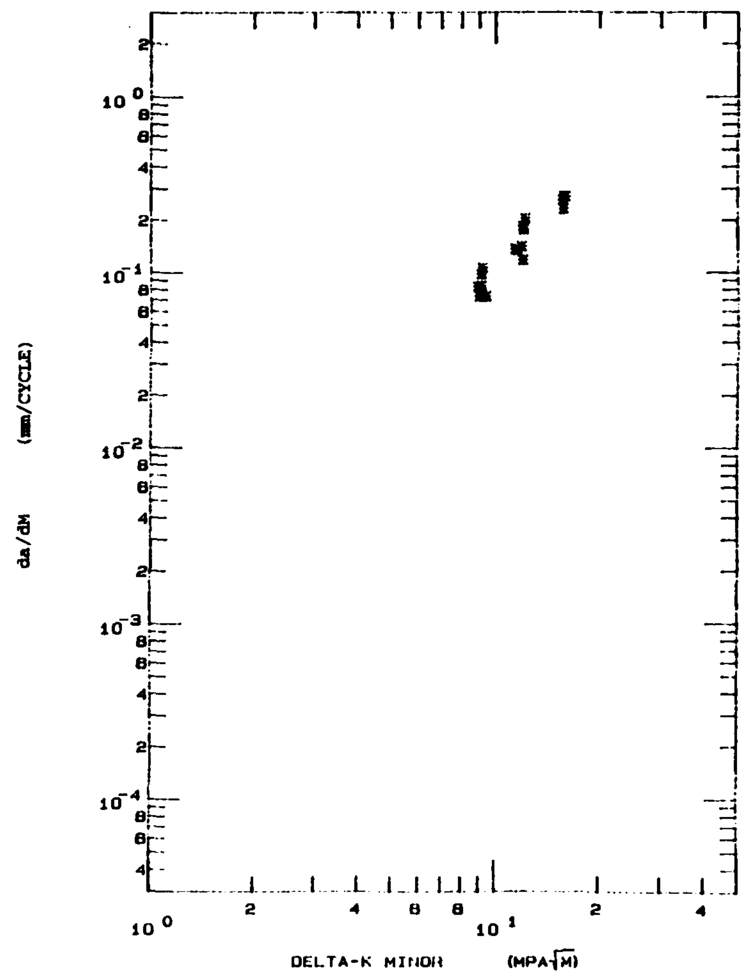

Figure 4.10. Test #116, Delta K Major = 20.0.

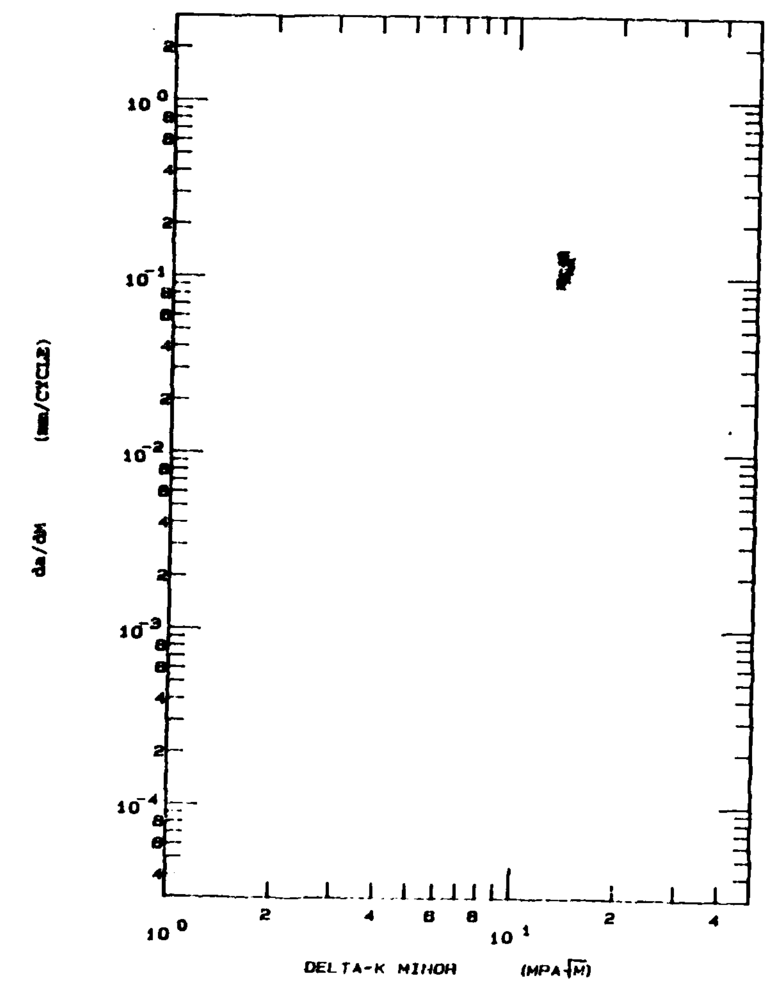

Figure 4.11. Test #117, Delta K Major = 15.0.

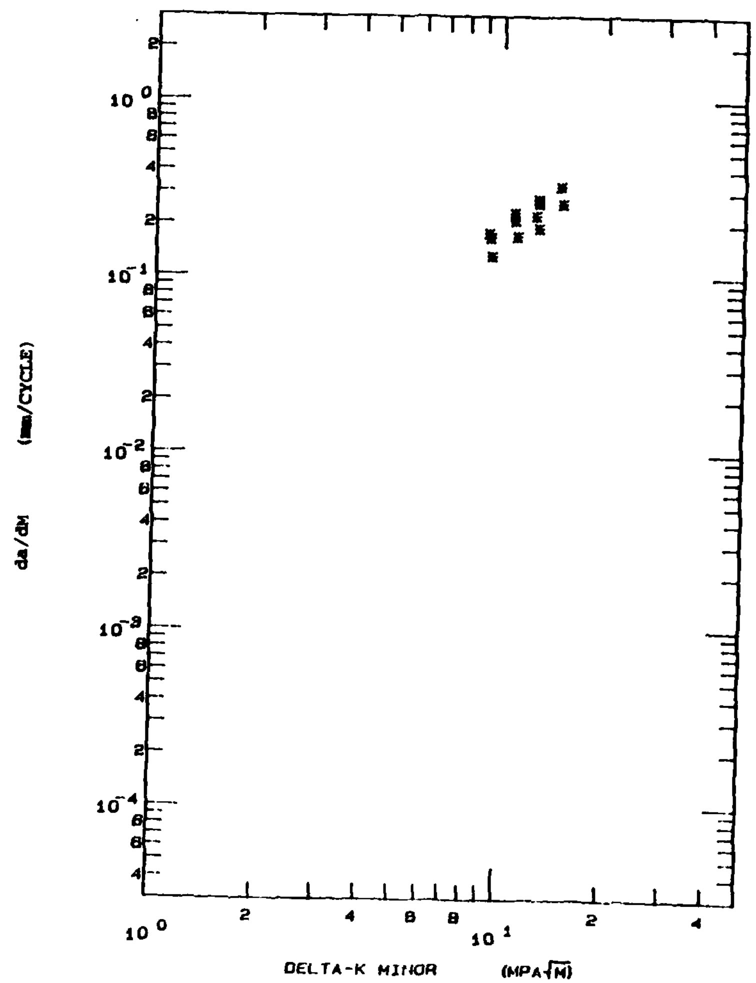

Figure 4.12. Test #119, Delta K Major = 25.0.

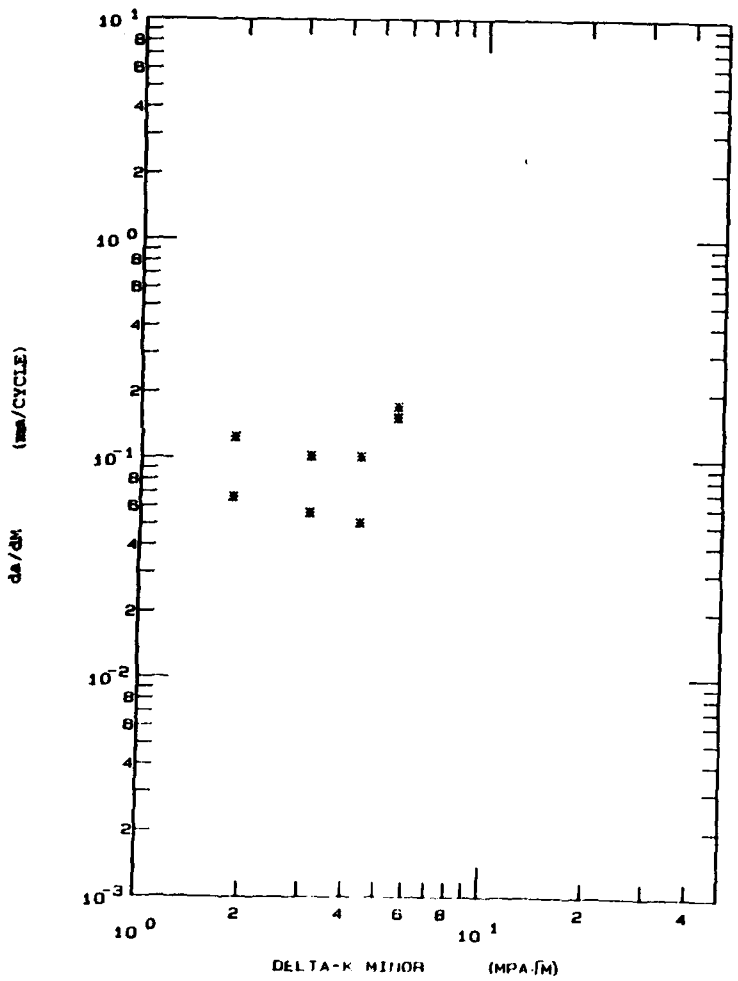

Figure 4.13. Test #120, Delta K Major = 25.0.

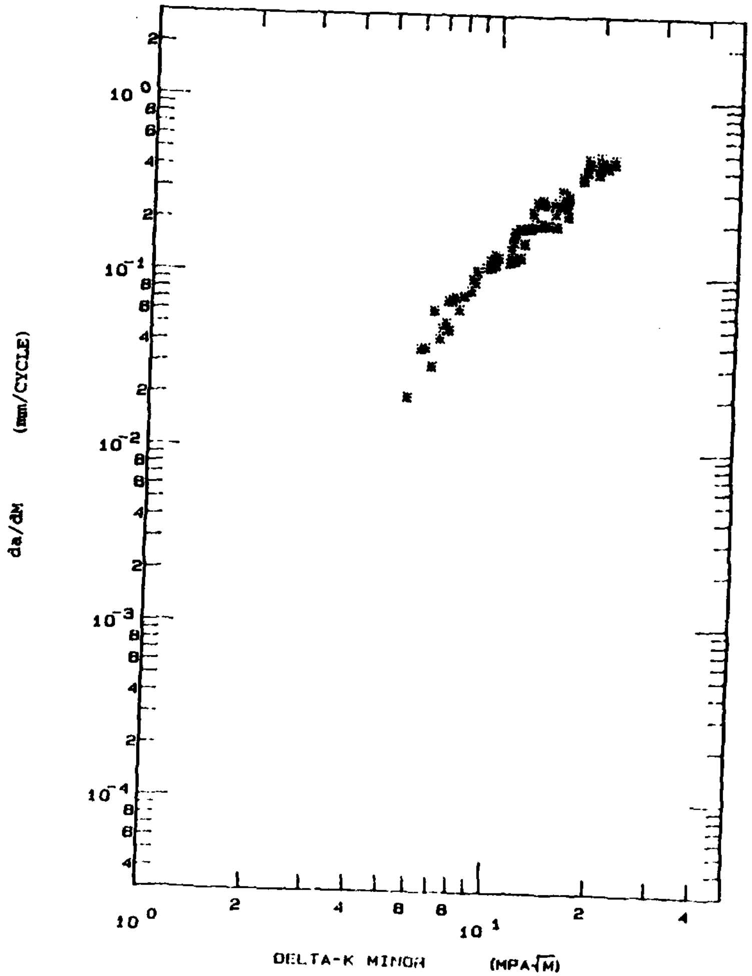

Figure 4.14. Test #121, Delta K Major = 20.0.

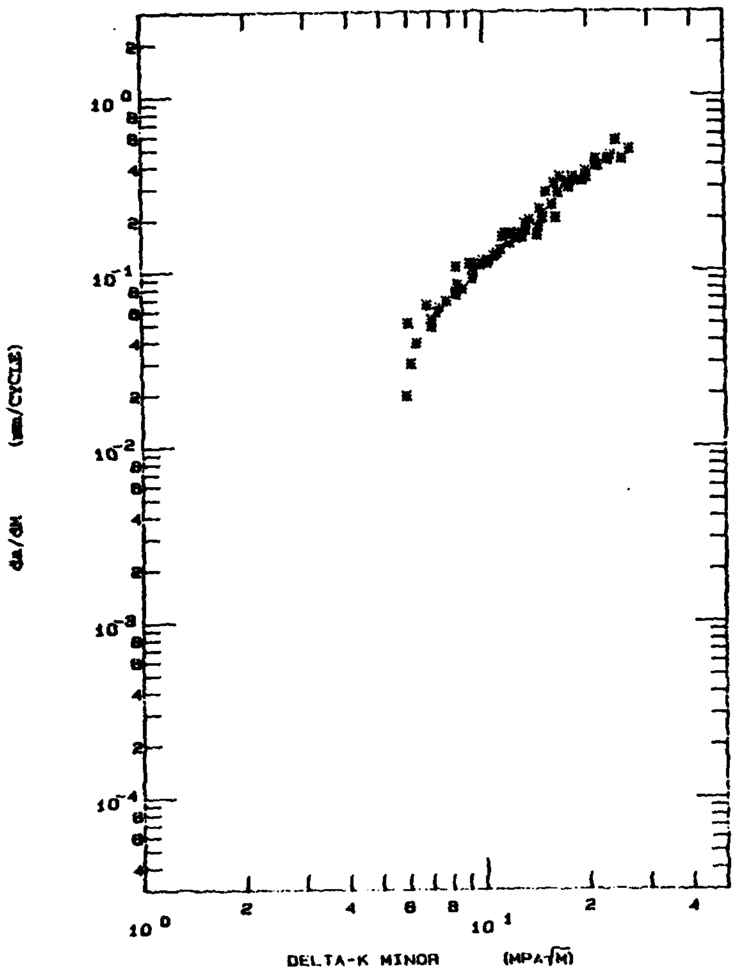

Figure 4.15. Test #122, Delta K Major = 25.0.

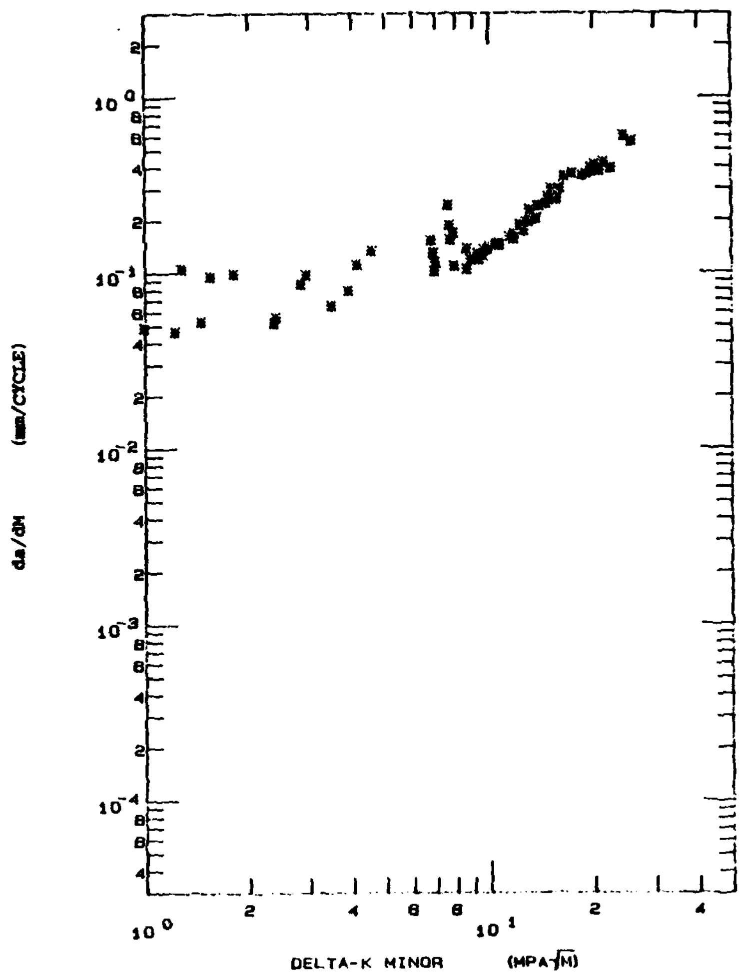

Figure 4.16. Test #123, Delta K Major = 30.0.

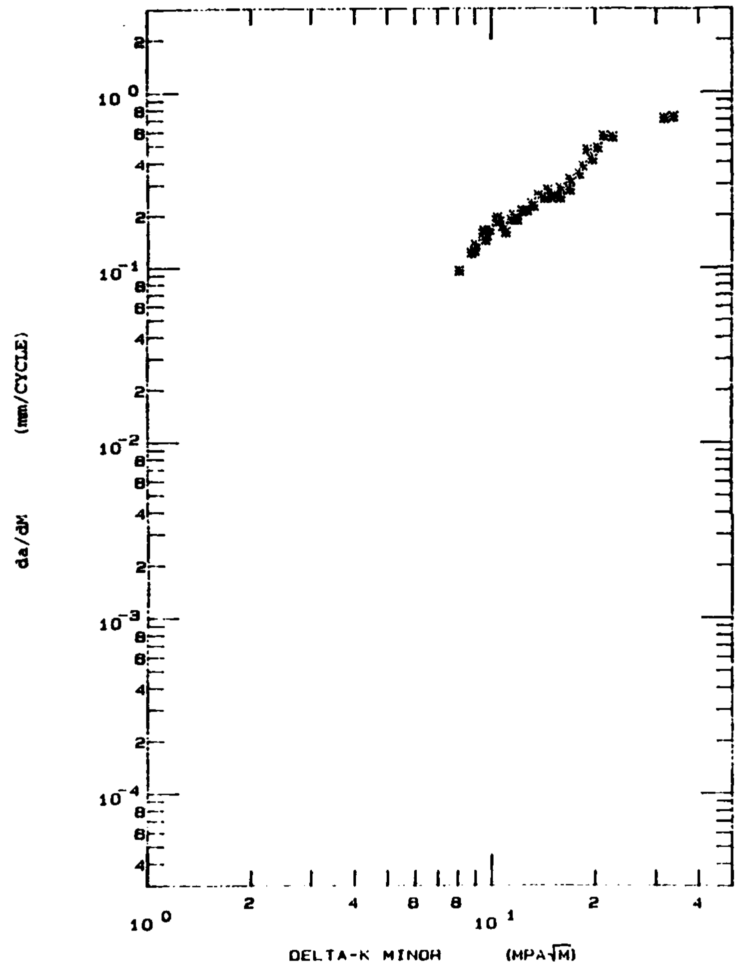

Figure 4.17. Test #124, Delta K Major = 35.0.

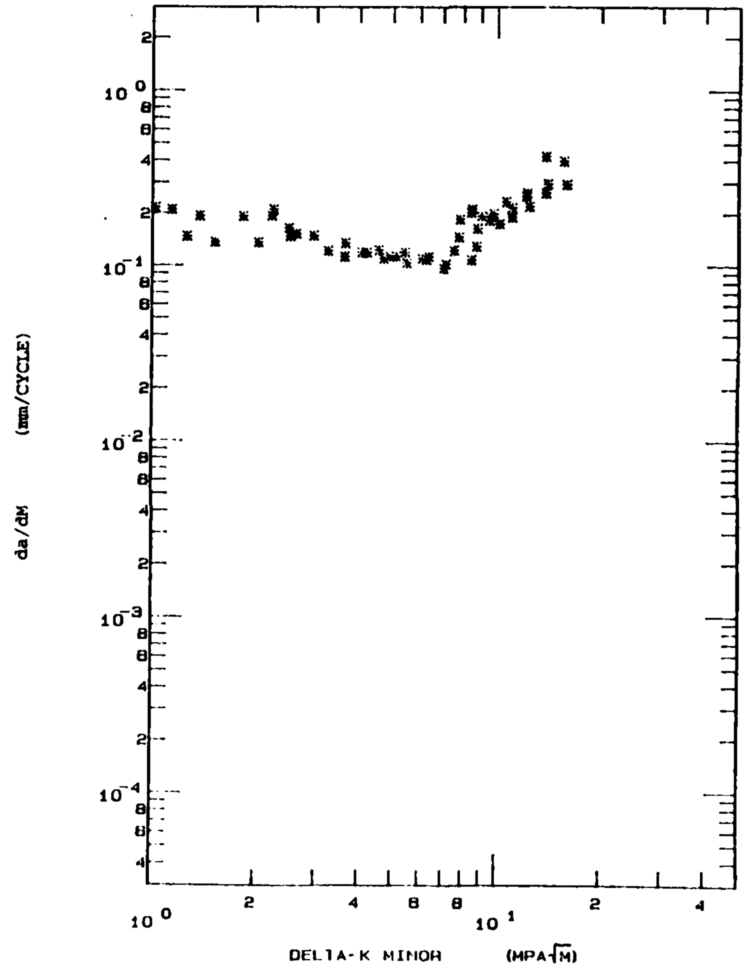

Figure 4.18. Test #125, Delta K Major = 40.0.

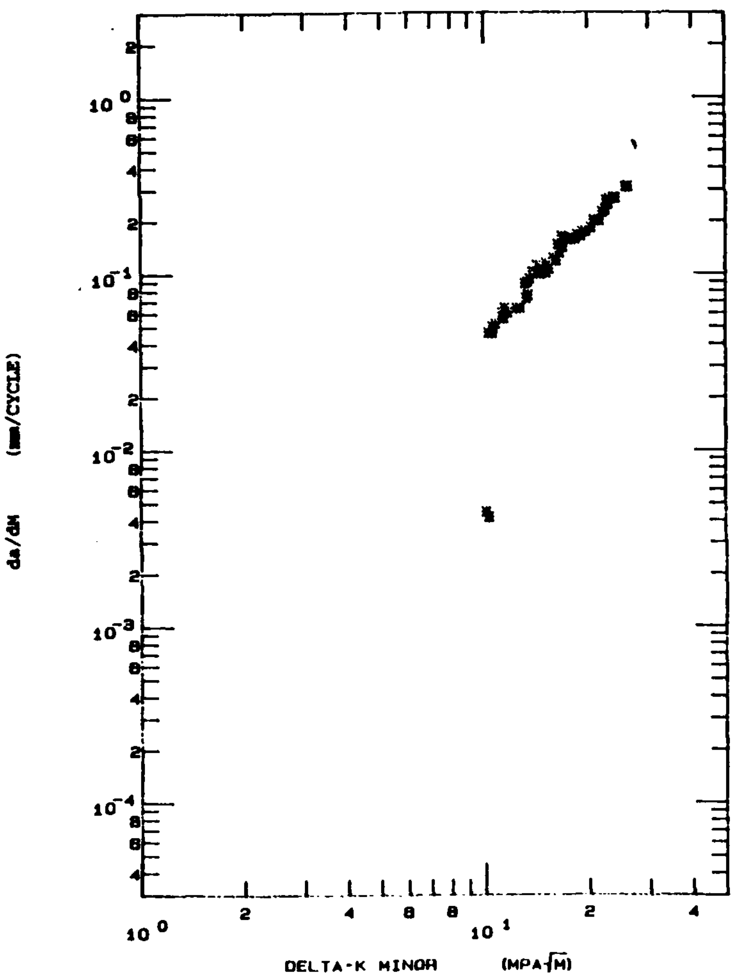

Figure 4.19. Test #126, Delta K Major = 15.0.

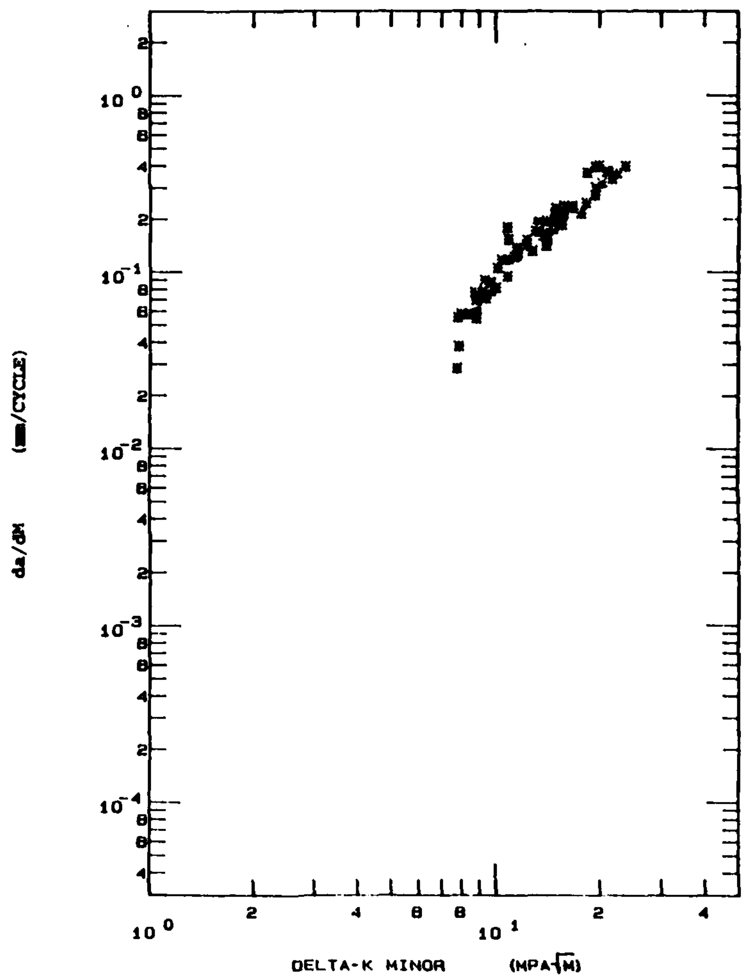

Figure 4.20. Test #127, Delta K Major = 20.0.

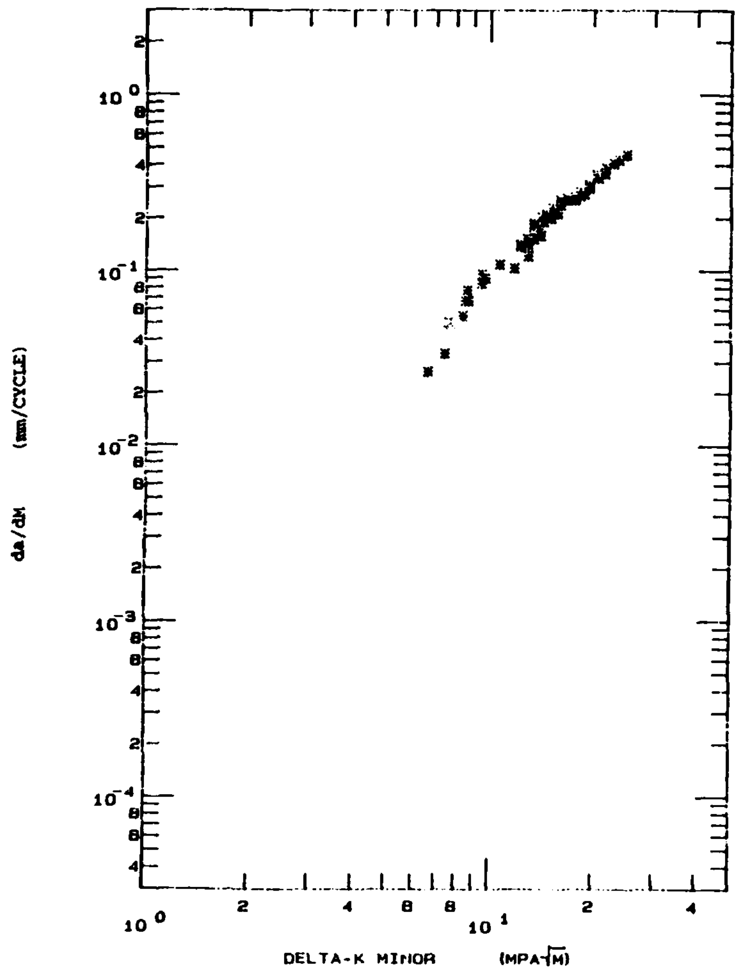

Figure 4.21. Test #128, Delta K Major = 20.0.

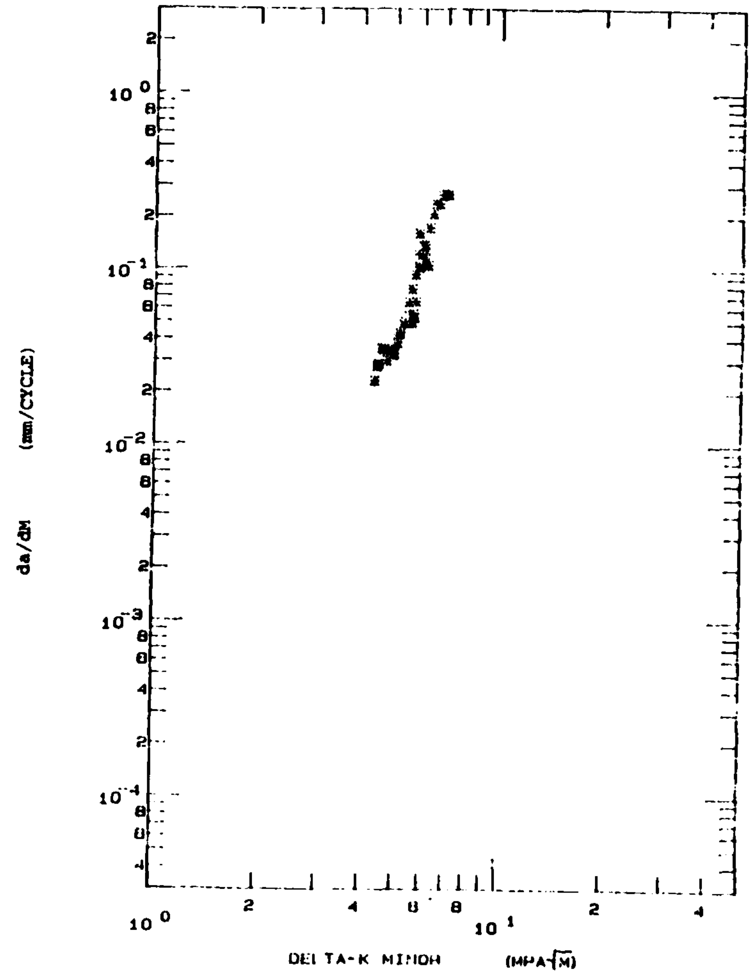

Figure 4.22. Test #132, Delta K Major = 25.0.

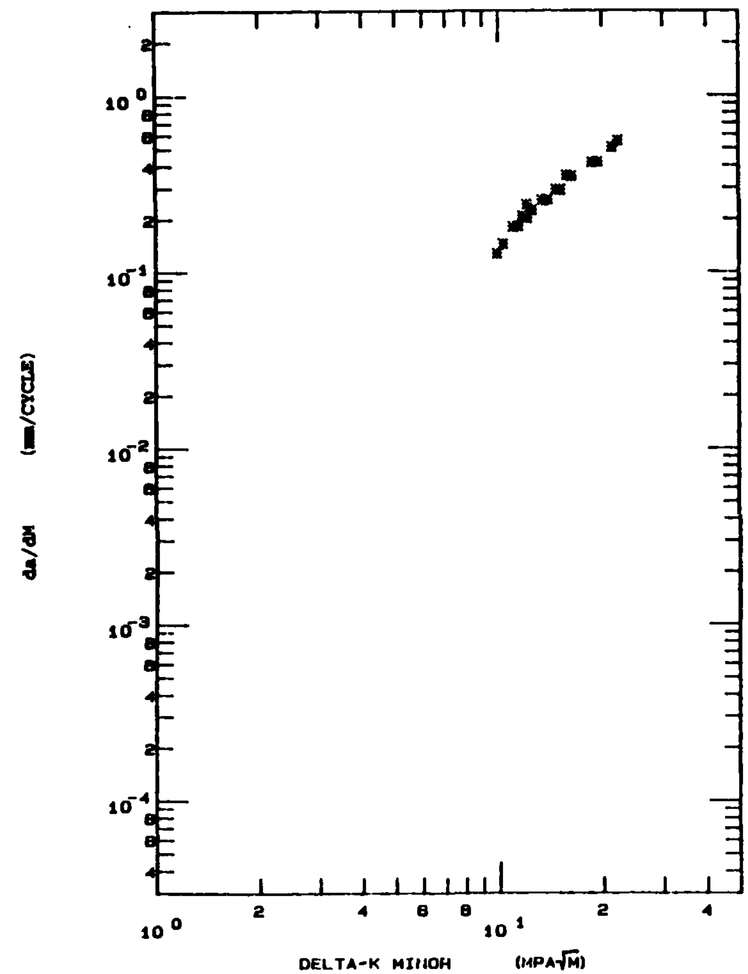

Figure 4.23. Test #140, Delta K Major = 25.0.

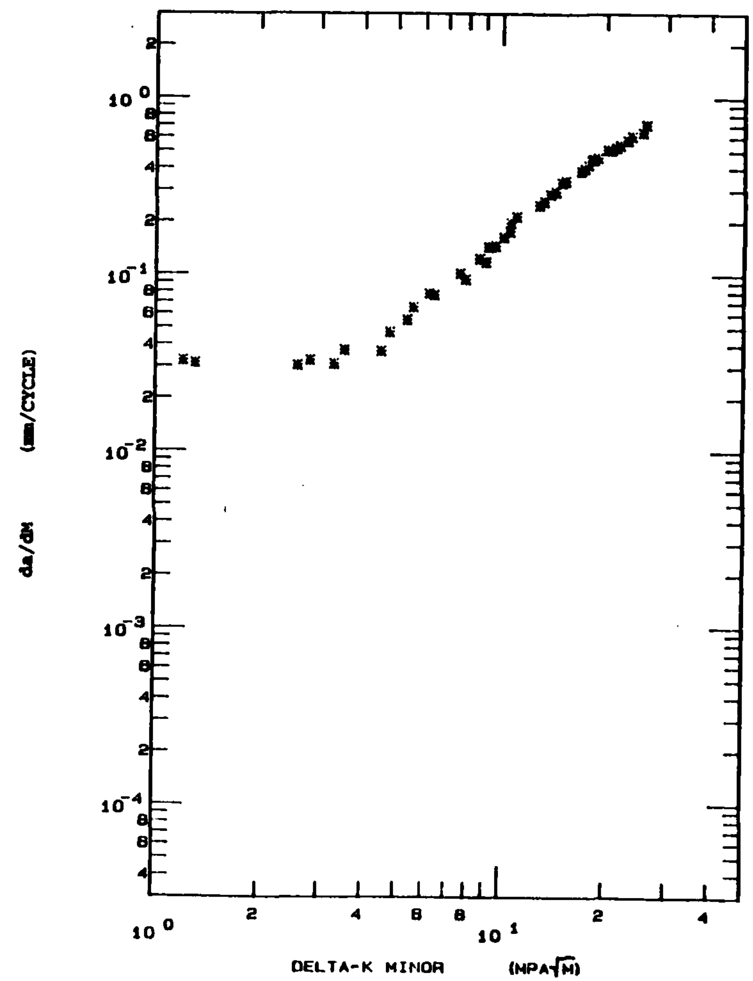

Figure 4.24. Test #141, Delta K Major = 30.0.

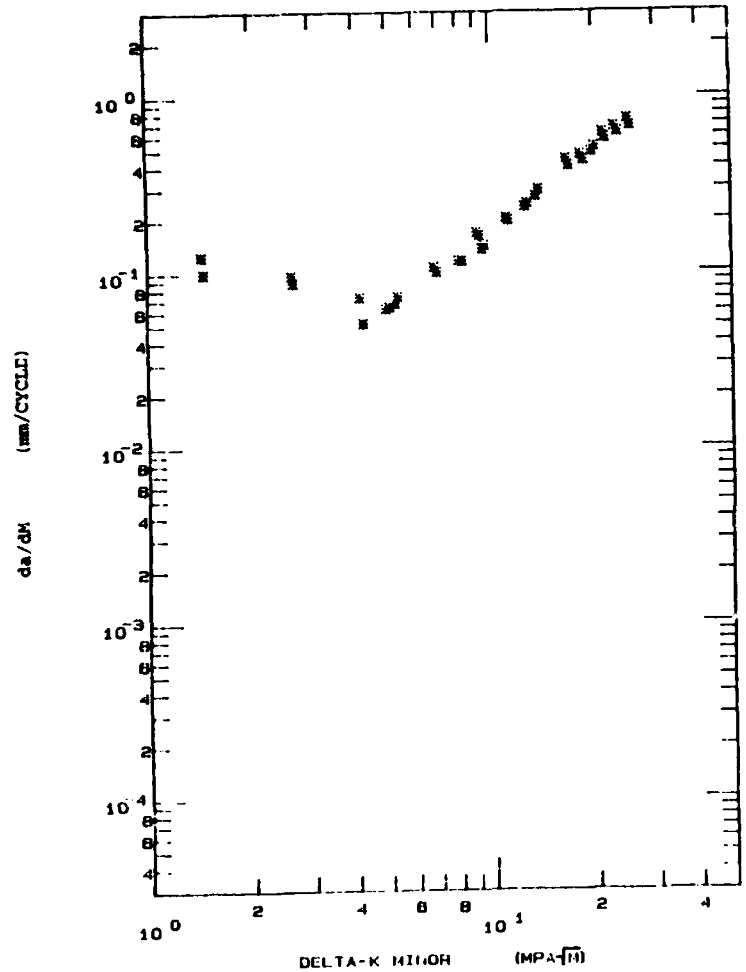

Figure 4.25. Test #142, Delta K Major = 35.0.

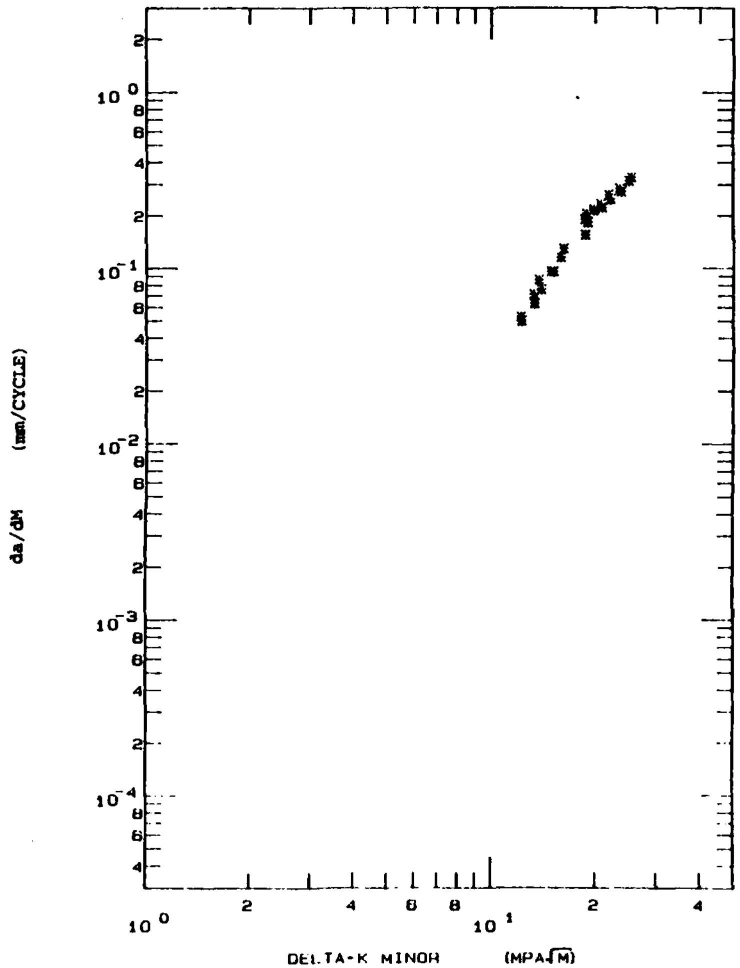

Figure 4.26. Test #143, Delta K Major = 15.0.

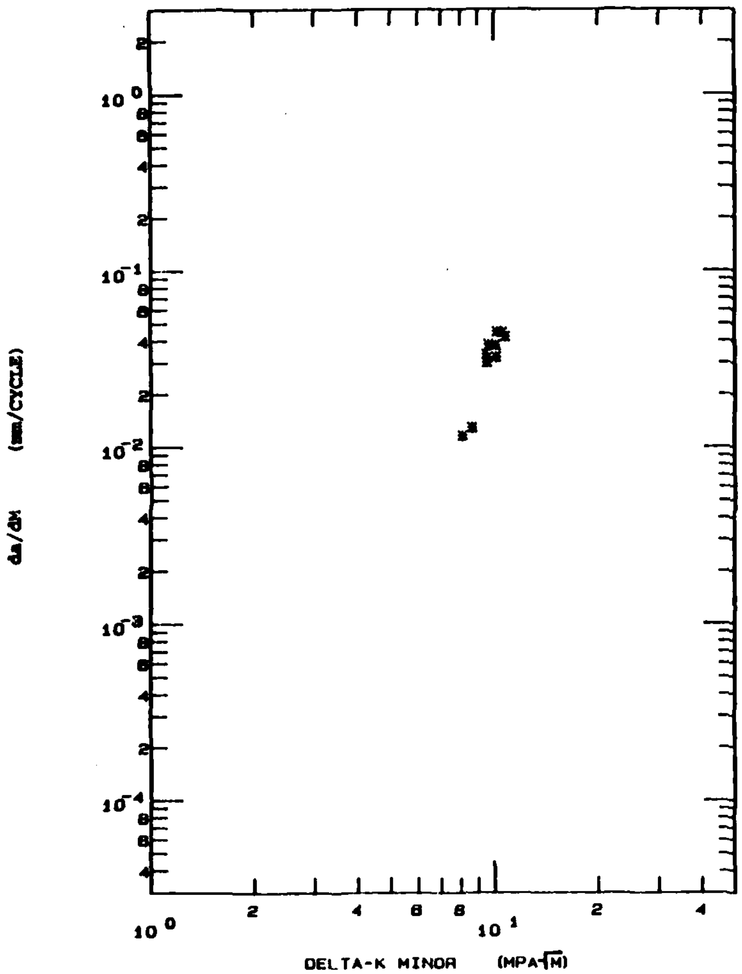

Figure 4.27. Test #144, Delta K Major = 15.0.

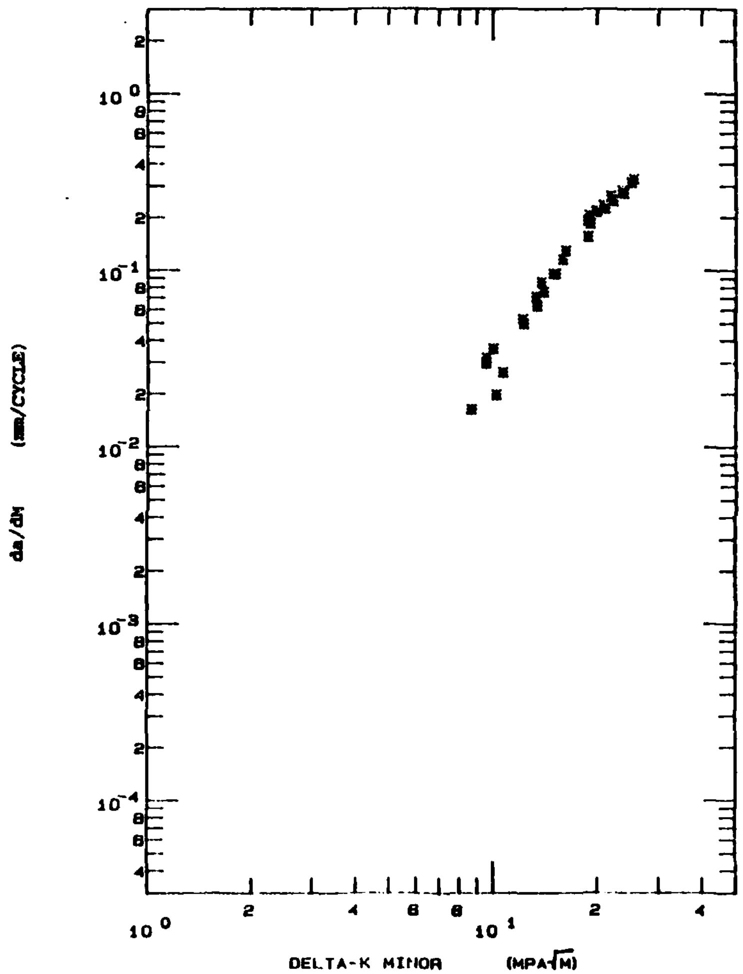

Figure 4.28. Tests 143/144, Delta K Major = 15.0.

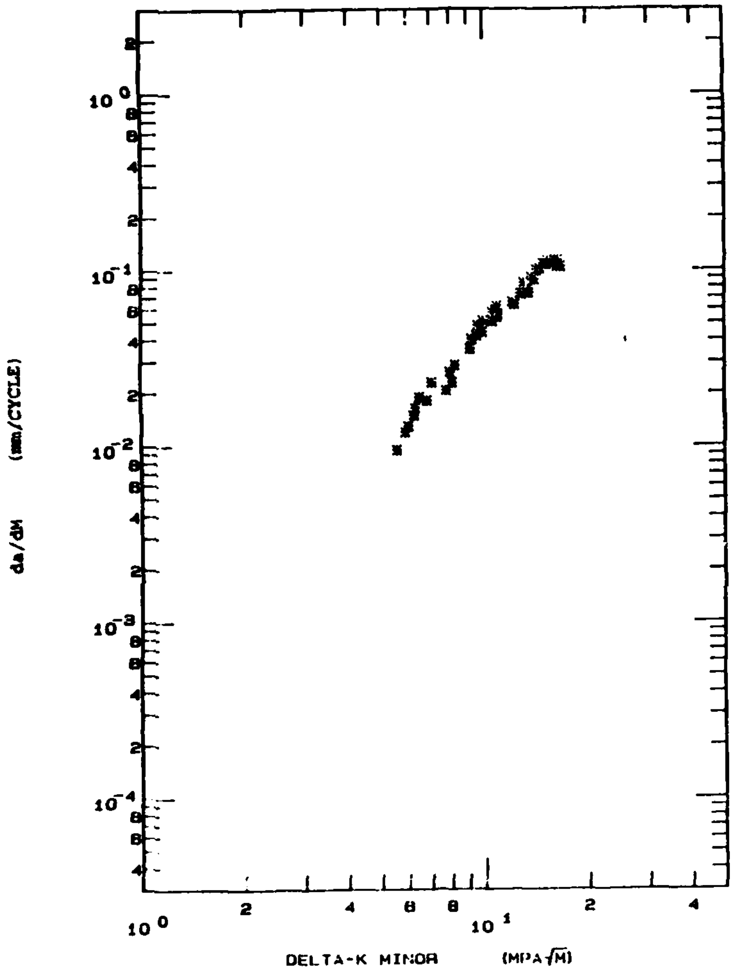

Figure 4.29. Test #145, Delta K Major = 20.0.

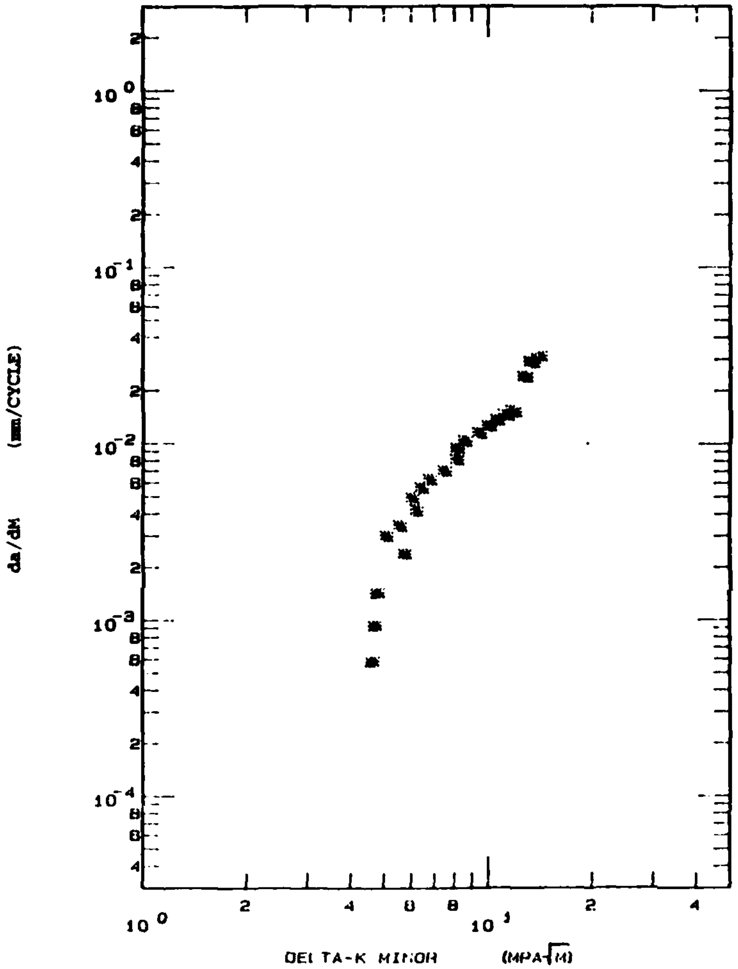

Figure 4.30. Test #146, Delta K Major = 20.0.

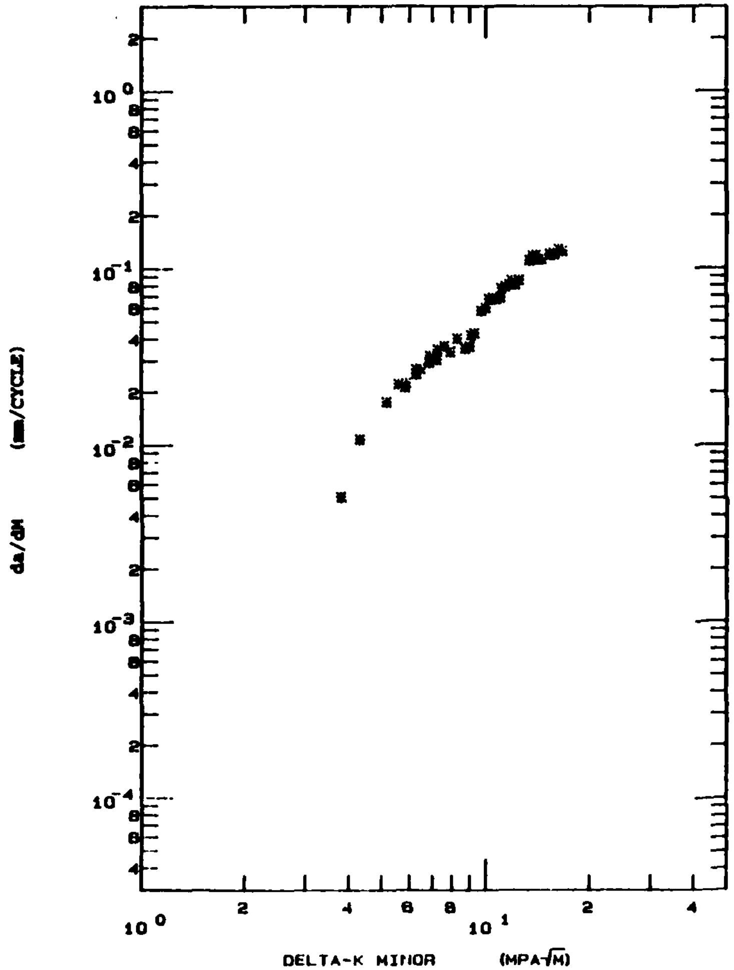

Figure 4.31. Test #147, Delta K Major = 25.0.

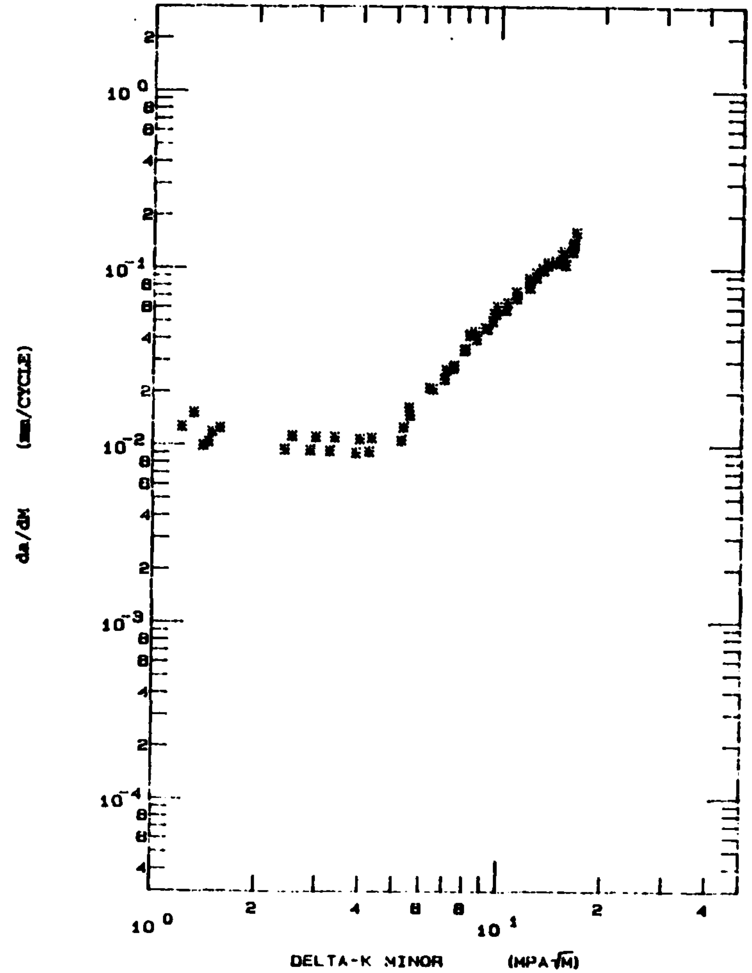

Figure 4.32. Test #148, Delta K Major = 30.0.

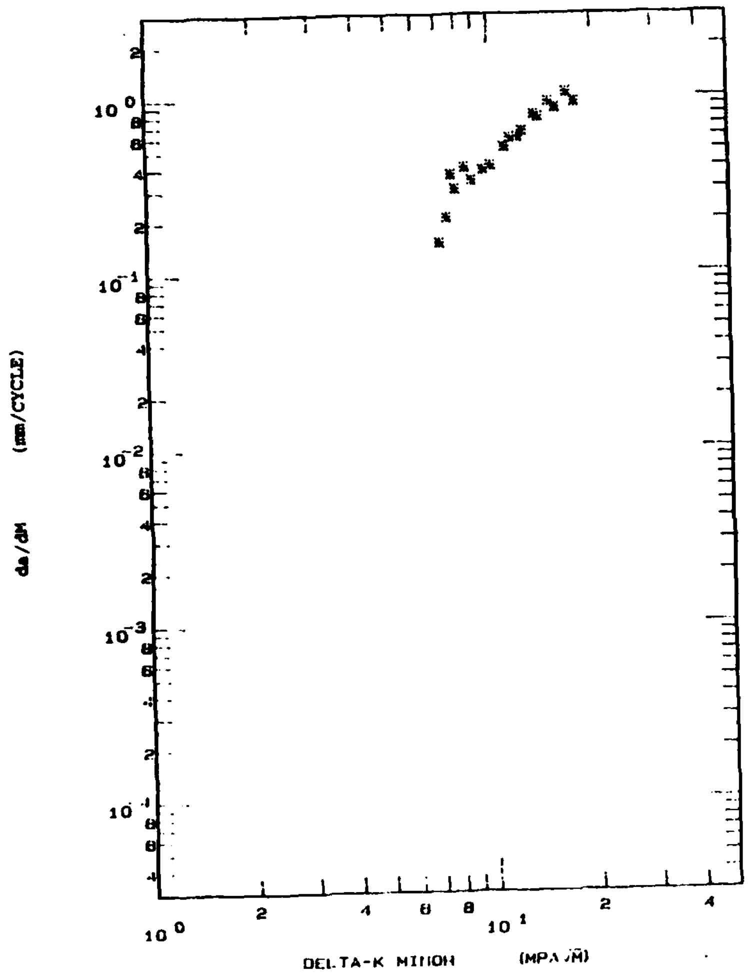

Figure 4.33. Test #149, Delta K Major = 25.0.

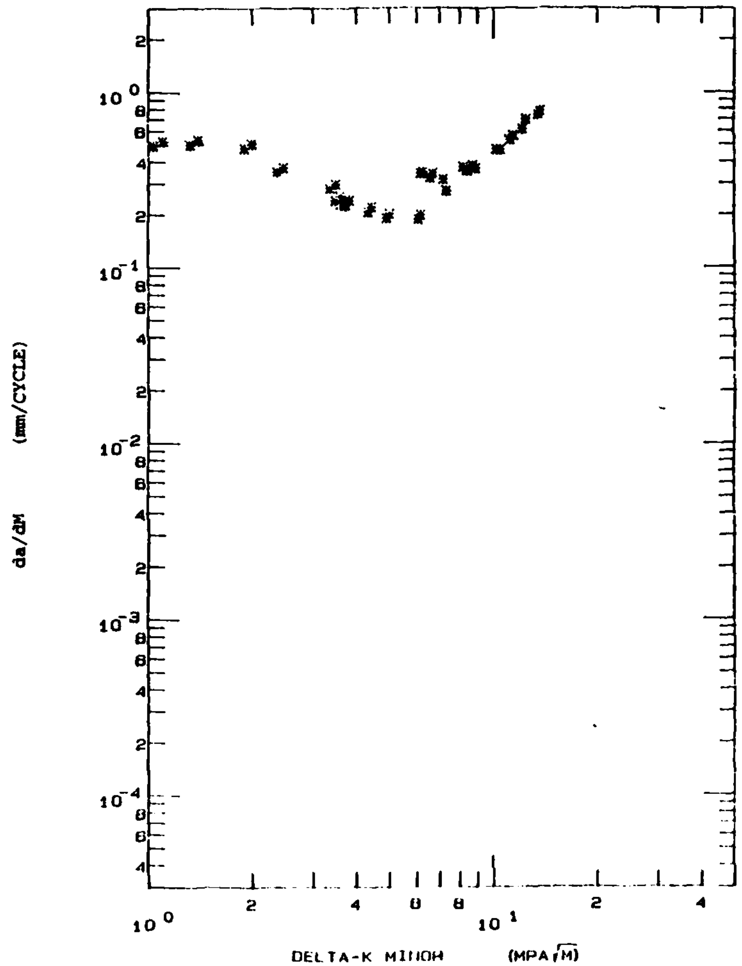

Figure 4.34. Test #150, Delta K Major = 25.0.

TABLE 4.1

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #104

	-------LEFT CRACK---------			.-------RIGHT CRACK--------		
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
15.00	27.77	.185E+01	.944E-01	26.50	.178E+01	.112E+00
18.00	28.52	.171E+01	.928E-01	27.50	.166E+01	.976E-01
23.00	27.49	.198E+01	.956E-01	26.70	.193E+01	.891E-01
28.00	27.59	.167E+01	.925E-01	26.71	.161E+01	.968E-01
31.00	28.01	.171E+01	.918E-01	26.92	.165E+01	.100E+00
36.00	27.84	.178E+01	.865E-01	27.03	.174E+01	.106E+00
39.00	28.01	.159E+01	.875E-01	27.52	.156E+01	.106E+00
42.00	28.01	.232E+00	.973E-01	27.57	.229E+00	.104E+00
47.00	28.11	.484E+00	.105E+00	27.75	.479E+00	.113E+00
50.00	27.80	.497E+00	.108E+00	27.56	.493E+00	.118E+00
53.00	27.77	.102E+01	.103E+00	27.58	.102E+01	.116E+00
57.00	27.87	.393E+01	.844E-01	27.76	.393E+01	.988E-01
66.00	27.52	.381E+01	.476E-01	27.64	.382E+01	.541E-01
94.00	27.61	.542E+01	.344E-01	27.74	.547E+01	.525E-01
100.00	27.18	.578E+01	.554E-01	27.45	.586E+01	.766E-01
108.00	27.56	.777E+01	.782E-01	28.34	.806E+01	.995E-01
115.00	27.35	.780E+01	.106E+00	28.43	.814E+01	.124E+00
118.00	27.39	.768E+01	.106E+00	28.59	.804E+01	.121E+00
121.00	26.90	.786E+01	.118E+00	28.24	.827E+01	.127E+00
124.00	27.01	.772E+01	.119E+00	28.45	.812E+01	.129E+00
127.00	27.05	.103E+02	.132E+00	28.43	.109E+02	.140E+00
131.00	27.08	.101E+02	.140E+00	28.60	.106E+02	.157E+00
133.00	27.24	.102E+02	.140E+00	28.92	.109E+02	.164E+00
138.00	26.86	.100E+02	.174E+00	28.65	.108E+02	.201E+00
141.00	26.37	.145E+02	.204E+00	28.45	.157E+02	.251E+00
144.00	26.86	.139E+02	.260E+00	29.28	.154E+02	.275E+00

TABLE 4.2

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #105

	-------LEFT CRACK---------			.-------RIGHT CRACK--------		
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
7.00	41.63	.256E+01	.137E+01	30.53	.196E+01	.152E+01
8.00	43.23	.322E+01	.153E+01	33.72	.254E+01	.140E+01
9.00	44.05	.264E+01	.208E+01	34.90	.209E+01	.230E+01
10.00	43.41	.723E+00	.226E+01	35.57	.605E+00	.263E+01
12.00	48.93	.410E+00	.444E+00	40.93	.342E+00	.467E+00
14.00	22.33	.827E+00	.364E-01	18.66	.692E+00	.185E+00

TABLE 4.3

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #107

	-------LEFT CRACK---------			.-------RIGHT CRACK--------		
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
166.00	33.68	.911E+01	.124E+00	34.82	.940E+01	.110E+00
168.00	33.88	.928E+01	.121E+00	35.10	.957E+01	.111E+00
171.00	33.97	.922E+01	.123E+00	34.91	.945E+01	.976E-01
174.00	34.42	.944E+01	.991E-01	35.19	.962E+01	.102E+00
176.00	34.15	.905E+01	.947E-01	34.86	.925E+01	.109E+00
178.00	34.29	.934E+01	.951E-01	35.08	.958E+01	.101E+00
180.00	33.95	.929E+01	.939E-01	34.90	.952E+01	.105E+00
183.00	33.67	.931E+01	.101E+00	34.51	.955E+01	.101E+00
189.00	34.72	.972E+01	.972E-01	35.66	.100E+02	.109E+00
194.00	33.75	.909E+01	.791E-01	34.92	.942E+01	.914E-01
196.00	33.62	.698E+01	.462E-01	34.87	.720E+01	.382E-01
224.00	33.25	.688E+01	.390E-01	34.45	.716E+01	.530E-01
232.00	33.54	.705E+01	.402E-01	35.14	.742E+01	.526E-01
239.00	33.31	.681E+01	.471E-01	35.36	.727E+01	.598E-01
250.00	32.52	.487E+01	.446E-01	34.73	.521E+01	.530E-01
255.00	32.65	.472E+01	.522E-01	34.98	.508E+01	.689E-01

TABLE 4.4

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #110

	-------LEFT CRACK---------			.-------RIGHT CRACK--------		
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
8.00	26.40	.232E+02	.401E+00	25.75	.226E+02	.770E+00
9.00	28.60	.238E+02	.570E+00	28.57	.243E+02	.709E+00
10.00	26.33	.226E+02	.560E+00	26.60	.226E+02	.401E+00
11.00	26.58	.219E+02	.252E+00	26.51	.218E+02	.227E+00
72.00	24.71	.547E+01	.394E-02	24.58	.544E+01	.553E-02

TABLE 4.5

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #111

	-------LEFT CRACK	---------	.-------RIGHT CRACK	--------		
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
10.00	38.60	.521E+01	.433E+00	41.58	.561E+01	.450E+00
12.00	37.90	.532E+01	.387E+00	40.84	.573E+01	.454E+00
14.00	37.91	.536E+01	.455E+00	40.98	.583E+01	.449E+00
15.00	38.05	.513E+01	.468E+00	41.56	.557E+01	.433E+00
16.00	38.83	.549E+01	.460E+00	42.10	.591E+01	.425E+00
17.00	38.29	.828E+01	.430E+00	40.96	.883E+01	.372E+00
19.00	37.95	.850E+01	.389E+00	40.76	.922E+01	.373E+00
20.00	38.08	.876E+01	.400E+00	41.28	.946E+01	.343E+00
22.00	37.74	.864E+01	.371E+00	40.43	.912E+01	.334E+00
23.00	38.97	.882E+01	.388E+00	40.93	.929E+01	.347E+00
25.00	38.51	.869E+01	.351E+00	40.88	.930E+01	.427E+00
27.00	38.21	.122E+02	.381E+00	41.14	.132E+02	.425E+00
29.00	37.66	.119E+02	.313E+00	40.80	.129E+02	.378E+00
30.00	37.90	.116E+02	.289E+00	41.21	.127E+02	.359E+00
32.00	36.91	.116E+02	.339E+00	40.65	.129E+02	.396E+00
33.00	36.35	.119E+02	.352E+00	40.62	.134E+02	.420E+00
35.00	37.15	.155E+02	.423E+00	41.65	.175E+02	.504E+00
36.00	36.88	.150E+02	.399E+00	41.90	.171E+02	.544E+00
37.00	37.40	.154E+02	.416E+00	43.28	.181E+02	.543E+00
38.00	36.91	.152E+02	.427E+00	43.71	.182E+02	.528E+00
39.00	36.32	.147E+02	.396E+00	43.66	.178E+02	.451E+00
40.00	35.51	.152E+02	.387E+00	43.23	.186E+02	.439E+00
41.00	35.58	.148E+02	.351E+00	43.92	.185E+02	.458E+00
42.00	34.02	.144E+02	.342E+00	42.82	.185E+02	.432E+00

TABLE 4.6

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #112

	-------LEFT CRACK---------			.-------RIGHT CRACK--------		
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
26.00	32.79	.130E+02	.168E+00	33.78	.136E+02	.213E+00
28.00	33.84	.127E+02	.229E+00	35.60	.134E+02	.236E+00
31.00	33.79	.130E+02	.240E+00	35.47	.136E+02	.213E+00
32.00	35.05	.131E+02	.232E+00	36.78	.137E+02	.228E+00
35.00	33.82	.132E+02	.280E+00	35.11	.137E+02	.309E+00
36.00	35.01	.133E+02	.237E+00	36.41	.139E+02	.243E+00
37.00	35.10	.133E+02	.277E+00	36.70	.139E+02	.328E+00
40.00	33.49	.130E+02	.239E+00	34.93	.135E+02	.241E+00
41.00	34.40	.132E+02	.224E+00	35.65	.137E+02	.225E+00
43.00	34.17	.133E+02	.226E+00	35.44	.139E+02	.234E+00
45.00	33.55	.129E+02	.214E+00	34.99	.135E+02	.218E+00
47.00	33.89	.132E+02	.220E+00	35.26	.137E+02	.221E+00
49.00	33.92	.130E+02	.235E+00	35.18	.136E+02	.232E+00
52.00	34.29	.133E+02	.239E+00	35.84	.138E+02	.252E+00
54.00	33.58	.134E+02	.231E+00	34.95	.139E+02	.256E+00
59.00	32.36	.132E+02	.221E+00	33.86	.140E+02	.239E+00
61.00	32.74	.127E+02	.209E+00	35.06	.136E+02	.245E+00
64.00	32.77	.131E+02	.201E+00	34.99	.139E+02	.215E+00
68.00	32.76	.129E+02	.199E+00	35.15	.140E+02	.249E+00
70.00	32.80	.127E+02	.207E+00	36.00	.141E+02	.240E+00
72.43	32.43	.126E+02	.225E+00	36.10	.141E+02	.248E+00
74.00	32.42	.129E+02	.203E+00	36.21	.145E+02	.228E+00
75.00	32.28	.128E+02	.185E+00	36.33	.145E+02	.219E+00
78.00	31.81	.125E+02	.169E+00	36.46	.145E+02	.223E+00
80.00	30.45	.129E+02	.168E+00	35.57	.153E+02	.235E+00
82.00	31.12	.121E+02	.177E+00	37.23	.147E+02	.240E+00
84.00	29.96	.119E+02	.160E+00	37.21	.149E+02	.246E+00
86.00	28.12	.119E+02	.142E+00	35.98	.157E+02	.225E+00

TABLE 4.7

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #113

	-------LEFT CRACK---------			.-------RIGHT CRACK--------		
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
10.00	30.34	.995E+01	.138E+00	28.59	.933E+01	.131E+00
13.00	30.08	.992E+01	.129E+00	28.23	.938E+01	.133E+00
16.00	30.27	.984E+01	.122E+00	28.72	.935E+01	.133E+00
20.00	29.81	.986E+01	.153E+00	28.46	.945E+01	.124E+00
22.00	29.90	.985E+01	.168E+00	28.52	.935E+01	.129E+00
25.00	30.23	.100E+02	.162E+00	28.60	.942E+01	.137E+00
27.00	29.93	.984E+01	.154E+00	28.01	.919E+01	.142E+00
31.00	29.99	.973E+01	.154E+00	28.23	.927E+01	.143E+00
33.00	30.06	.102E+02	.151E+00	28.65	.960E+01	.132E+00
38.00	30.79	.103E+02	.153E+00	28.87	.957E+01	.114E+00
42.00	29.62	.997E+01	.145E+00	27.27	.917E+01	.118E+00
48.00	29.09	.975E+01	.163E+00	26.91	.904E+01	.175E+00
55.00	30.77	.170E+02	.234E+00	28.58	.159E+02	.292E+00
56.00	30.66	.166E+02	.247E+00	28.63	.156E+02	.290E+00
62.00	29.69	.164E+02	.351E+00	28.32	.159E+02	.296E+00
64.00	30.44	.168E+02	.375E+00	29.34	.161E+02	.333E+00
65.00	31.19	.169E+02	.376E+00	29.55	.160E+02	.309E+00
67.00	31.01	.169E+02	.341E+00	29.28	.159E+02	.339E+00

TABLE 4.8

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #114

N	-------LEFT CRACK	---------	.	-------RIGHT CRACK	--------	
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
9.00	26.01	.986E+01	.171E+00	30.16	.114E+02	.172E+00
11.00	26.26	.990E+01	.176E+00	30.21	.113E+02	.171E+00
13.00	26.42	.101E+02	.176E+00	30.15	.115E+02	.178E+00
15.00	26.66	.102E+02	.176E+00	30.29	.115E+02	.176E+00
17.00	26.63	.103E+02	.170E+00	30.21	.116E+02	.170E+00
19.00	26.76	.101E+02	.174E+00	30.18	.113E+02	.167E+00
21.00	26.82	.101E+02	.180E+00	30.10	.114E+02	.171E+00
23.00	26.90	.103E+02	.192E+00	30.11	.115E+02	.187E+00
25.00	27.05	.105E+02	.234E+00	30.14	.117E+02	.220E+00
26.00	27.47	.132E+02	.244E+00	30.54	.146E+02	.231E+00
28.00	27.21	.135E+02	.268E+00	30.14	.149E+02	.257E+00
30.00	27.50	.134E+02	.264E+00	30.31	.148E+02	.258E+00
32.00	27.66	.135E+02	.263E+00	30.43	.148E+02	.263E+00
33.00	27.52	.137E+02	.266E+00	30.24	.151E+02	.265E+00
35.00	27.84	.135E+02	.274E+00	30.59	.148E+02	.268E+00
36.00	27.76	.136E+02	.255E+00	30.48	.149E+02	.258E+00
38.00	27.66	.135E+02	.259E+00	30.31	.148E+02	.265E+00
40.00	27.42	.138E+02	.273E+00	30.16	.152E+02	.278E+00

TABLE 4.9

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #115

	-------LEFT CRACK	---------	.	-------RIGHT CRACK	--------	
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
14.00	24.14	.546E+01	.519E-01	25.79	.585E+01	.691E-01
17.00	23.58	.519E+01	.870E-01	25.30	.557E+01	.914E-01
19.00	23.88	.527E+01	.993E-01	25.70	.566E+01	.108E+00
21.00	24.23	.784E+01	.122E+00	26.00	.841E+01	.129E+00
24.00	23.89	.104E+02	.128E+00	25.60	.111E+02	.142E+00
27.00	23.87	.103E+02	.135E+00	25.67	.111E+02	.150E+00
28.00	23.46	.100E+02	.141E+00	25.24	.108E+02	.152E+00
32.00	22.79	.101E+02	.161E+00	24.53	.109E+02	.173E+00
33.00	23.25	.101E+02	.165E+00	25.04	.109E+02	.178E+00
34.00	23.72	.102E+02	.160E+00	25.56	.110E+02	.173E+00
35.00	23.62	.102E+02	.150E+00	25.46	.110E+02	.162E+00
37.00	23.50	.101E+02	.136E+00	25.34	.109E+02	.147E+00
38.00	23.32	.992E+01	.149E+00	25.17	.107E+02	.158E+00
39.00	23.45	.101E+02	.156E+00	25.31	.109E+02	.164E+00
41.00	32.12	.101E+02	.133E+00	24.96	.109E+02	.136E+00

TABLE 4.10

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #116

	-------LEFT CRACK---------			-------RIGHT CRACK--------		
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
32.00	20.61	.110E+02	.103E+00	20.39	.109E+02	.105E+00
34.00	20.91	.113E+02	.138E+00	20.70	.112E+02	.140E+00
35.00	20.98	.114E+02	.111E+00	20.78	.114E+02	.118E+00
37.00	21.32	.117E+02	.105E+00	21.12	.117E+02	.116E+00
40.00	20.48	.113E+02	.105E+00	20.33	.112E+02	.121E+00
41.00	19.74	.110E+02	.107E+00	19.65	.110E+02	.130E+00
43.00	20.24	.113E+02	.131E+00	20.21	.113E+02	.158E+00
44.00	20.43	.112E+02	.136E+00	20.47	.113E+02	165E+00
46.00	20.67	.115E+02	.145E+00	20.77	.116E+02	.174E+00
47.00	20.88	.119E+02	.141E+00	21.05	.120E+02	.168E+00
50.00	19.98	.110E+02	.138E+00	20.22	.112E+02	.154E+00
52.00	19.92	.110E+02	.118E+00	20.25	.112E+02	.126E+00
54.00	19.71	.857E+01	.979E-01	20.03	.872E+01	.101E+00
57.00	19.68	.865E+01	.816E-01	19.98	.881E+01	.860E-01
59.00	19.83	.896E+01	.725E-01	20.17	.913E+01	.818E-01
62.00	20.02	.887E+01	.689E-01	20.39	.905E+01	.751E-01
64.00	19.68	.882E+01	.663E-01	20.07	.901E+01	.709E-01
67.00	19.74	.857E+01	.696E-01	20.15	.875E+01	.744E-01
69.00	19.48	.866E+01	.715E-01	19.90	.885E+01	.765E-01
71.00	19.72	.858E+01	.811E-01	20.16	.878E+01	.867E-01
73.00	19.66	.868E+01	.843E-01	20.10	.889E+01	.902E-01
75.00	19.89	.879E+01	.873E-01	20.36	.901E+01	.933E-01
77.00	20.16	.887E+01	.746E-01	20.66	.908E+01	.724E-01
79.00	20.59	.886E+01	.687E-01	21.11	.908E+01	.714E-01
83.00	19.51	.860E+01	.658E-01	19.97	.886E+01	.779E-01
86.00	19.84	.904E+01	.564E-01	20.33	.934E+01	.737E-01
88.00	19.49	.883E+01	.664E-01	20.13	.919E+01	.911E-01
92.00	19.10	.874E+01	.718E-01	19.83	.911E+01	.896E-01
94.00	19.29	.864E+01	.783E-01	20.08	.902E+01	.900E-01
96.00	19.79	.896E+01	.939E-01	20.66	.937E+01	.108E+00
98.00	19.38	.864E+01	.751E-01	20.26	.905E+01	.843E-01
100.00	19.82	.876E+01	.678E-01	20.76	.919E+01	.736E-01
103.00	18.81	.823E+01	.610E-01	19.73	.864E+01	.641E-01
106.00	19.33	.856E+01	.578E-01	20.29	.899E+01	.592E-01
109.00	18.82	.868E+01	.630E-01	19.77	.913E+01	.645E-01
112.00	19.07	.878E+01	.703E-01	20.05	.924E+01	.720E-01
114.00	19.33	.891E+01	.860E-01	20.33	.939E+01	.906E-01
116.00	19.57	.909E+01	.115E+00	20.59	.961E+01	.125E+00
118.00	19.81	.877E+01	.149E+00	20.88	.929E+01	.166E+00
119.00	18.80	.166E+02	.185E+00	19.88	.177E+02	.209E+00
120.00	19.05	.166E+02	.203E+00	20.21	.177E+02	.227E+00
121.00	18.62	.162E+02	.214E+00	19.80	.173E+02	.240E+00
122.00	18.93	.165E+02	.225E+00	20.18	.177E+02	.252E+00
123.00	19.49	.169E+02	.255E+00	20.86	.182E+02	.286E+00
124.00	19.25	.158E+02	.206E+00	20.68	.172E+02	.276E+00
125.00	19.50	.157E+02	.161E+00	21.03	.173E+02	.233E+00
127.00	19.00	.154E+02	.117E+00	20.79	.174E+02	.211E+00
129.00	18.82	.152E+02	.808E-01	20.93	.174E+02	.153E+00
132.00	17.46	.889E+01	.685E-01	19.90	.104E+02	.116E+00
136.00	17.53	.874E+01	.587E-01	20.49	.103E+02	.948E-01
139.00	17.38	.830E+01	.571E-01	20.45	.992E+01	.743E-01
142.00	17.58	.808E+01	.430E-01	20.88	.977E+01	.683E-01
145.00	17.13	.796E+01	.366E-01	20.59	.984E+01	.631E-01
151.00	16.30	.813E+01	.360E-01	19.94	.104E+02	.656E-01

TABLE 4.11

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #117

	-------LEFT CRACK	---------	.	-------RIGHT CRACK	--------	
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
17.00	12.72	.135E+02	.133E+00	15.30	.162E+02	.984E-01
18.00	13.02	.137E+02	.135E+00	15.55	.163E+02	.101E+00
19.00	12.73	.134E+02	.130E+00	15.13	.159E+02	.977E-01
20.00	12.85	.135E+02	.127E+00	15.19	.159E+02	.125E+00
21.00	13.24	.138E+02	.117E+00	15.57	.162E+02	.150E+00
22.00	13.22	.138E+02	.101E+00	15.56	.163E+02	.154E+00
23.00	13.01	.133E+02	.928E-01	15.42	.158E+02	.144E+00
24.00	12.82	.134E+02	.100E+00	15.22	.159E+02	.126E+00
25.00	12.84	.135E+02	.103E+00	15.23	.160E+02	.120E+00
26.00	13.04	.135E+02	.104E+00	15.47	.161E+02	.125E+00
27.00	12.96	.136E+02	.105E+00	15.38	.161E+02	.129E+00
28.00	13.02	.137E+02	.108E+00	15.46	.162E+02	.133E+00
29.00	13.17	.137E+02	.112E+00	15.63	.163E+02	.138E+00
30.00	13.37	.140E+02	.113E+00	15.89	.166E+02	.140E+00
31.00	13.10	.139E+02	.117E+00	15.58	.165E+02	.145E+00
32.00	13.23	.140E+02	.122E+00	15.74	.167E+02	.150E+00
33.00	13.37	.142E+02	.123E+00	15.91	.169E+02	.151E+00

TABLE 4.12

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #119

	-------LEFT CRACK	---------	.	-------RIGHT CRACK	--------	
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
8.00	21.33	.222E+02	.338E+00	25.76	.267E+02	.334E+00
11.00	20.94	.128E+02	.210E+00	25.20	.153E+02	.223E+00
12.00	21.72	.128E+02	.257E+00	26.06	.154E+02	.276E+00
13.00	20.96	.127E+02	.280E+00	25.08	.151E+02	.301E+00
14.00	20.79	.128E+02	.268E+00	24.84	.153E+02	.289E+00
15.00	21.03	.126E+02	.258E+00	25.09	.150E+02	.279E+00
16.00	20.84	.126E+02	.227E+00	24.83	.150E+02	.247E+00
17.00	21.69	.128E+02	.190E+00	25.83	.153E+02	.207E+00
18.00	21.25	.934E+01	.159E+00	25.30	.111E+02	.174E+00
20.00	20.96	.938E+01	.130E+00	24.95	.112E+02	.141E+00
21.00	21.07	.934E+01	.131E+00	25.08	.111E+02	.142E+00
23.00	21.06	.917E+01	.369E+00	25.07	.109E+02	.376E+00

TABLE 4.13

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #121

	-------LEFT CRACK---------			-------RIGHT CRACK--------		
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
5.00	23.49	.218E+02	.467E+00	23.43	.216E+02	.443E+00
6.00	22.97	.207E+02	.419E+00	22.72	.205E+02	.448E+00
7.00	22.77	.196E+02	.382E+00	22.88	.198E+02	.480E+00
8.00	23.11	.196E+02	.414E+00	23.36	.199E+02	.447E+00
9.00	22.90	.183E+02	.463E+00	23.15	.185E+02	.432E+00
10.00	22.76	.180E+02	.400E+00	23.02	.181E+02	.393E+00
11.00	22.85	.176E+02	.373E+00	22.96	.177E+02	.355E+00
13.00	22.27	.159E+02	.246E+00	22.46	.160E+02	.220E+00
14.00	22.51	.159E+02	.276E+00	22.68	.160E+02	.283E+00
15.00	22.52	.157E+02	.286E+00	22.51	.157E+02	.294E+00
16.00	22.57	.152E+02	.250E+00	22.70	.154E+02	.303E+00
17.00	22.43	.147E+02	.249E+00	22.70	.149E+02	.261E+00
18.00	22.85	.147E+02	.226E+00	23.13	.149E+02	.191E+00
19.00	22.43	.139E+02	.254E+00	22.61	.140E+02	.194E+00
20.00	22.52	.134E+02	.260E+00	22.61	.134E+02	.193E+00
21.00	22.56	.135E+02	.269E+00	22.54	.134E+02	.200E+00
22.00	22.52	.130E+02	.263E+00	22.39	.129E+02	.196E+00
23.00	22.85	.127E+02	.227E+00	22.60	.125E+02	.188E+00
24.00	22.76	.125E+02	.187E+00	22.42	.123E+02	.186E+00
25.00	22.66	.120E+02	.151E+00	22.32	.118E+02	.182E+00
26.00	22.53	.117E+02	.126E+00	22.29	.116E+02	.184E+00
28.00	22.27	.113E+02	.121E+00	22.16	.113E+02	.176E+00
30.00	22.47	.111E+02	.121E+00	22.54	.112E+02	.166E+00
32.00	22.57	.111E+02	.122E+00	22.81	.112E+02	.154E+00
34.00	22.48	.109E+02	.119E+00	22.83	.110E+02	.139E+00
36.00	22.02	.975E+01	.118E+00	22.40	.993E+01	.130E+00
38.00	22.23	.991E+01	.114E+00	22.66	.101E+02	.125E+00
40.00	22.05	.963E+01	.111E+00	22.51	.984E+01	.123E+00
42.00	21.98	.934E+01	.109E+00	22.49	.956E+01	.120E+00
44.00	22.02	.857E+01	.937E-01	22.57	.879E+01	.104E+00
46.00	21.88	.844E+01	.803E-01	22.47	.868E+01	.899E-01
49.00	21.75	.786E+01	.627E-01	22.38	.809E+01	.754E-01
52.00	22.04	.723E+01	.525E-01	22.74	.748E+01	.716E-01
56.00	21.74	.735E+01	.480E-01	22.57	.767E+01	.734E-01
59.00	21.64	.693E+01	.426E-01	22.67	.729E+01	.699E-01
63.00	21.21	.628E+01	.379E-01	22.41	.667E+01	.619E-01
67.00	21.25	.659E+01	.297E-01	22.66	.705E+01	.488E-01
75.00	20.75	.566E+01	.196E-01	22.32	.611E+01	.374E-01

TABLE 4.14

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #122

	-------LEFT CRACK	---------	.	-------RIGHT CRACK	--------	
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
5.00	26.77	.277E+02	.533E+00	23.97	.252E+02	.537E+00
7.00	26.10	.244E+02	.415E+00	23.79	.226E+02	.502E+00
8.00	27.12	.252E+02	.432E+00	24.96	.233E+02	.455E+00
9.00	25.81	.229E+02	.439E+00	23.98	.211E+02	.432E+00
10.00	26.52	.229E+02	.429E+00	24.52	.211E+02	.396E+00
11.00	26.62	.215E+02	.398E+00	24.52	.198E+02	.365E+00
12.00	26.09	.198E+02	.339E+00	24.12	.182E+02	.340E+00
13.00	25.60	.192E+02	.325E+00	23.63	.177E+02	.299E+00
14.00	25.96	.187E+02	.326E+00	23.94	.173E+02	.319E+00
15.00	25.67	.181E+02	.344E+00	23.64	.167E+02	.341E+00
16.00	25.83	.173E+02	.320E+00	23.83	.160E+02	.315E+00
17.00	25.91	.165E+02	.276E+00	23.92	.152E+02	.282E+00
18.00	25.71	.158E+02	.237E+00	23.68	.145E+02	.225E+00
19.00	25.92	.162E+02	.200E+00	23.91	.149E+02	.200E+00
20.00	25.50	.148E+02	.212E+00	23.51	.136E+02	.195E+00
21.00	25.65	.144E+02	.181E+00	23.61	.132E+02	.186E+00
22.00	25.14	.143E+02	.159E+00	23.09	.132E+02	.169E+00
24.00	25.10	.129E+02	.155E+00	23.11	.119E+02	.163E+00
26.00	25.23	.124E+02	.152E+00	23.29	.115E+02	.164E+00
27.00	25.52	.126E+02	.165E+00	23.49	.116E+02	.161E+00
28.00	25.34	.123E+02	.160E+00	23.35	.113E+02	.156E+00
29.00	25.36	.119E+02	.143E+00	23.39	.109E+02	.127E+00
31.00	25.48	.112E+02	.132E+00	23.43	.102E+02	.111E+00
33.00	25.20	.107E+02	.122E+00	23.06	.976E+01	.107E+00
35.00	25.37	.103E+02	.115E+00	23.14	.934E+01	.108E+00
38.00	25.13	.996E+01	.113E+00	22.88	.905E+01	.109E+00
40.00	25.32	.915E+01	.111E+00	23.03	.829E+01	.105E+00
42.00	25.53	.928E+01	.985E-01	23.19	.837E+01	.828E-01
44.00	25.74	.922E+01	.907E-01	23.29	.829E+01	.754E-01
47.00	25.46	.867E+01	.791E-01	22.90	.775E+01	.672E-01
51.00	25.77	.829E+01	.729E-01	23.07	.738E+01	.617E-01
54.00	25.34	.678E+01	.639E-01	22.63	.600E+01	.500E-01
57.00	25.96	.724E+01	.582E-01	23.06	.634E+01	.386E-01
62.00	25.48	.704E+01	.525E-01	22.45	.613E+01	.294E-01
65.00	26.21	.700E+01	.479E-01	22.89	.595E+01	.193E-01

TABLE 4.15

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #123

	-------LEFT CRACK---------			-------RIGHT CRACK--------		
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
6.00	29.87	.245E+02	.602E+00	31.74	.258E+02	.560E+00
8.00	29.78	.214E+02	.424E+00	31.33	.224E+02	.392E+00
9.00	29.62	.198E+02	.376E+00	30.99	.208E+02	.378E+00
10.00	29.37	.191E+02	.366E+00	30.79	.201E+02	.411E+00
11.00	29.46	.186E+02	.358E+00	30.98	.196E+02	.393E+00
12.00	29.17	.165E+02	.351E+00	30.77	.174E+02	.363E+00
13.00	28.68	.151E+02	.298E+00	30.28	.160E+02	.298E+00
14.00	29.22	.149E+02	.257E+00	30.79	.157E+02	.261E+00
15.00	28.64	.139E+02	.239E+00	30.16	.147E+02	.267E+00
16.00	28.73	.137E+02	.201E+00	30.34	.146E+02	.245E+00
17.00	28.83	.130E+02	.196E+00	30.55	.138E+02	.239E+00
18.00	28.58	.123E+02	.186E+00	30.38	.131E+02	.226E+00
19.00	28.66	.118E+02	.165E+00	30.54	.127E+02	.194E+00
20.00	28.44	.117E+02	.154E+00	30.40	.126E+02	.173E+00
22.00	27.78	.106E+02	.147E+00	29.77	.114E+02	.160E+00
24.00	27.70	.992E+01	.135E+00	29.74	.107E+02	.143E+00
25.00	28.05	.922E+01	.128E+00	30.14	.993E+01	.140E+00
26.00	27.89	.959E+01	.125E+00	29.98	.104E+02	.144E+00
28.00	27.72	.885E+01	.118E+00	29.87	.957E+01	.136E+00
29.00	27.96	.857E+01	.104E+00	30.23	.929E+01	.119E+00
31.00	27.97	.789E+01	.109E+00	30.29	.860E+01	.136E+00
33.00	27.58	.697E+01	.114E+00	29.93	.766E+01	.153E+00
35.00	27.47	.689E+01	.129E+00	30.02	.766E+01	.186E+00
37.00	27.91	.676E+01	.152E+00	30.85	.760E+01	.241E+00
38.00	28.51	.690E+01	.102E+00	31.80	.787E+01	.169E+00
41.00	26.15	.389E+01	.787E-01	29.75	.455E+01	.133E+00
46.00	26.19	.348E+01	.652E-01	30.47	.413E+01	.111E+00
49.00	25.95	.236E+01	.516E-01	30.50	.284E+01	.865E-01
53.00	26.49	.239E+01	.558E-01	31.62	.292E+01	.974E-01
56.00	25.36	.145E+01	.530E-01	30.74	.180E+01	.989E-01
59.00	26.23	.122E+01	.461E-01	32.21	.154E+01	.950E-01
62.00	24.61	.989E+00	.488E-01	30.77	.127E+01	.105E+00

TABLE 4.16

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #124

N	LEFT CRACK DKMAJOR	LEFT CRACK DKMINOR	LEFT CRACK DADN	RIGHT CRACK DKMAJOR	RIGHT CRACK DKMINOR	RIGHT CRACK DADN
5.00	34.51	.316E+02	.710E+00	37.41	.337E+02	.728E+00
9.00	34.19	.211E+02	.567E+00	36.43	.225E+02	.560E+00
10.00	33.91	.190E+02	.472E+00	35.96	.203E+02	.486E+00
11.00	34.35	.184E+02	.383E+00	36.55	.196E+02	.416E+00
12.00	34.17	.169E+02	.321E+00	36.51	.180E+02	.343E+00
13.00	33.74	.159E+02	.285E+00	36.02	.169E+02	.278E+00
14.00	33.36	.149E+02	.250E+00	35.59	.159E+02	.250E+00
15.00	33.50	.143E+02	.251E+00	35.72	.153E+02	.261E+00
16.00	33.23	.137E+02	.259E+00	35.45	.146E+02	.278E+00
17.00	33.39	.133E+02	.224E+00	35.70	.143E+02	.248E+00
18.00	33.29	.122E+02	.210E+00	35.65	.131E+02	.232E+00
19.00	33.03	.118E+02	.191E+00	35.42	.127E+02	.211E+00
20.00	33.24	.114E+02	.187E+00	35.70	.123E+02	.210E+00
21.00	33.03	.108E+02	.171E+00	35.54	.116E+02	.199E+00
22.00	33.11	.110E+02	.158E+00	35.70	.119E+02	.187E+00
24.00	33.28	.973E+01	.152E+00	36.02	.106E+02	.182E+00
25.00	32.93	.944E+01	.155E+00	35.77	.103E+02	.186E+00
26.00	33.00	.955E+01	.161E+00	35.93	.104E+02	.193E+00
27.00	33.29	.901E+01	.134E+00	36.36	.988E+01	.164E+00
28.00	32.67	.875E+01	.121E+00	35.79	.963E+01	.143E+00
30.00	32.88	.807E+01	.949E-01	36.14	.896E+01	.124E+00

TABLE 4.17

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #125

	-------LEFT CRACK	----------	.	--------RIGHT CRACK	--------	
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
6.00	38.92	.153E+02	.398E+00	34.17	.134E+02	.421E+00
7.00	40.55	.158E+02	.376E+00	36.67	.139E+02	.409E+00
8.00	40.73	.154E+02	.333E+00	35.95	.136E+02	.342E+00
10.00	39.91	.134E+02	.261E+00	35.38	.119E+02	.261E+00
12.00	39.65	.120E+02	.233E+00	35.05	.106E+02	.224E+00
13.00	40.97	.124E+02	.205E+00	36.17	.109E+02	.206E+00
14.00	40.20	.110E+02	.190E+00	35.46	.968E+01	.198E+00
15.00	39.65	.101E+02	.173E+00	35.02	.892E+01	.192E+00
16.00	39.59	.941E+01	.176E+00	35.01	.832E+01	.196E+00
17.00	39.81	.933E+01	.186E+00	35.24	.826E+01	.207E+00
19.00	39.73	.876E+01	.162E+00	35.22	.777E+01	.183E+00
20.00	39.84	.864E+01	.144E+00	35.38	.768E+01	.162E+00
22.00	40.26	.833E+01	.107E+00	35.81	.742E+01	.122E+00
24.00	39.52	.692E+01	.964E-01	35.20	.617E+01	.108E+00
26.00	39.84	.702E+01	.102E+00	35.52	.626E+01	.112E+00
28.00	39.62	.600E+01	.109E+00	35.35	.536E+01	.119E+00
30.00	39.22	.540E+01	.103E+00	35.01	.483E+01	.113E+00
32.00	39.47	.503E+01	.113E+00	35.26	.449E+01	.123E+00
34.00	39.44	.464E+01	.109E+00	35.25	.415E+01	.119E+00
36.00	39.43	.399E+01	.119E+00	35.25	.357E+01	.112E+00
38.00	39.23	.358E+01	.138E+00	35.09	.319E+01	.122E+00
40.00	39.48	.290E+01	.155E+00	35.08	.257E+01	.168E+00
41.00	39.59	.243E+01	.164E+00	35.02	.215E+01	.190E+00
43.00	40.38	.250E+01	.146E+00	35.94	.224E+01	.207E+00
44.00	40.51	.200E+01	.135E+00	36.28	.179E+01	.193E+00
46.00	39.83	.149E+01	.146E+00	35.83	.135E+01	.208E+00
47.00	40.34	.124E+01	.162E+00	36.46	.112E+01	.230E+00
48.00	40.83	.698E+00	.188E+00	37.08	.635E+00	.268E+00
49.00	40.94	.996E+00	.214E+00	37.37	.912E+00	.304E+00
50.00	40.95	.145E+00	.238E+00	37.58	.134E+00	.338E+00

TABLE 4.18

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #126

N	LEFT CRACK DKMAJOR	LEFT CRACK DKMINOR	LEFT CRACK DADN	RIGHT CRACK DKMAJOR	RIGHT CRACK DKMINOR	RIGHT CRACK DADN
4.00	15.26	.270E+02	.332E+00	15.46	.274E+02	.339E+00
6.00	15.14	.250E+02	.287E+00	15.37	.253E+02	.283E+00
7.00	14.80	.236E+02	.270E+00	14.99	.239E+02	.268E+00
9.00	14.83	.225E+02	.259E+00	15.00	.229E+02	.265E+00
10.00	15.18	.223E+02	.229E+00	15.37	.227E+02	.248E+00
11.00	14.99	.215E+02	.200E+00	15.21	.219E+02	.223E+00
12.00	14.49	.203E+02	.181E+00	14.73	.207E+02	.199E+00
14.00	14.45	.192E+02	.171E+00	14.72	.196E+02	.173E+00
15.00	14.47	.186E+02	.166E+00	14.75	.190E+02	.162E+00
17.00	14.69	.180E+02	.158E+00	14.94	.183E+02	.156E+00
19.00	14.66	.175E+02	.155E+00	14.88	.179E+02	.158E+00
20.00	14.70	.164E+02	.145E+00	14.97	.168E+02	.161E+00
21.00	14.41	.166E+02	.131E+00	14.69	.169E+02	.141E+00
22.00	14.60	.159E+02	.122E+00	14.89	.162E+02	.118E+00
24.00	14.50	.151E+02	.114E+00	14.80	.154E+02	.106E+00
26.00	14.43	.148E+02	.105E+00	14.70	.151E+02	.101E+00
28.00	14.62	.142E+02	.101E+00	14.86	.145E+02	.996E-01
30.00	14.34	.139E+02	.102E+00	14.59	.142E+02	.111E+00
32.00	14.43	.135E+02	.930E-01	14.71	.138E+02	.101E+00
34.00	14.74	.131E+02	.872E-01	15.03	.133E+02	.889E-01
37.00	14.82	.132E+02	.721E-01	15.13	.134E+02	.748E-01
39.00	14.80	.124E+02	.629E-01	15.10	.127E+02	.633E-01
42.00	14.53	.113E+02	.590E-01	14.83	.115E+02	.634E-01
45.00	14.61	.114E+02	.552E-01	14.93	.117E+02	.597E-01
48.00	14.16	.106E+02	.495E-01	14.48	.108E+02	.514E-01
51.00	14.39	.103E+02	.456E-01	14.73	.106E+02	.455E-01
55.00	14.43	.101E+02	.441E-02	14.77	.103E+02	.414E-02

TABLE 4.19

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #127

	LEFT CRACK			RIGHT CRACK		
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
5.00	18.83	.223E+02	.363E+00	19.95	.237E+02	.398E+00
7.00	18.44	.202E+02	.321E+00	19.67	.216E+02	.337E+00
8.00	18.12	.195E+02	.396E+00	19.54	.208E+02	.369E+00
9.00	18.66	.199E+02	.404E+00	19.96	.211E+02	.370E+00
10.00	18.57	.184E+02	.366E+00	19.57	.194E+02	.302E+00
11.00	18.72	.182E+02	.247E+00	19.86	.193E+02	.272E+00
12.00	18.23	.166E+02	.237E+00	19.31	.176E+02	.216E+00
13.00	17.82	.156E+02	.227E+00	18.83	.165E+02	.233E+00
14.00	17.78	.148E+02	.211E+00	18.76	.157E+02	.237E+00
15.00	17.66	.140E+02	.194E+00	18.69	.149E+02	.230E+00
16.00	18.43	.147E+02	.183E+00	19.59	.157E+02	.214E+00
17.00	18.33	.146E+02	.176E+00	19.50	.155E+02	.186E+00
18.00	17.63	.132E+02	.187E+00	18.77	.140E+02	.141E+00
19.00	17.58	.134E+02	.191E+00	18.72	.141E+02	.153E+00
21.00	17.97	.132E+02	.179E+00	18.96	.139E+02	.158E+00
23.00	18.45	.133E+02	.170E+00	19.36	.140E+02	.165E+00
25.00	18.42	.123E+02	.142E+00	19.43	.130E+02	.170E+00
26.00	18.11	.128E+02	.132E+00	19.14	.137E+02	.160E+00
29.00	18.00	.116E+02	.136E+00	19.09	.123E+02	.152E+00
30.00	17.94	.109E+02	.152E+00	19.14	.115E+02	.138E+00
32.00	17.96	.108E+02	.179E+00	19.15	.113E+02	.122E+00
34.00	18.13	.109E+02	.118E+00	19.15	.115E+02	.124E+00
36.00	18.22	.108E+02	.942E-01	19.03	.116E+02	.128E+00
41.00	18.09	.965E+01	.777E-01	19.16	.104E+02	.117E+00
43.00	17.76	.938E+01	.706E-01	19.21	.101E+02	.105E+00
46.00	17.65	.928E+01	.895E-01	19.04	.100E+02	.816E-01
48.00	17.88	.892E+01	.737E-01	19.25	.967E+01	.860E-01
50.00	17.78	.881E+01	.613E-01	19.19	.962E+01	.873E-01
53.00	17.67	.846E+01	.576E-01	19.23	.927E+01	.777E-01
56.00	17.47	.834E+01	.569E-01	19.17	.919E+01	.734E-01
59.00	17.23	.794E+01	.578E-01	18.91	.878E+01	.687E-01
61.00	17.50	.780E+01	.553E-01	19.27	.869E+01	.766E-01
64.00	17.35	.785E+01	.378E-01	19.23	.882E+01	.697E-01
67.00	17.38	.773E+01	.284E-01	19.42	.883E+01	.543E-01

TABLE 4.20

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #128

	LEFT CRACK			RIGHT CRACK		
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
6.00	19.87	.236E+02	.429E+00	20.94	.249E+02	.459E+00
8.00	19.66	.216E+02	.385E+00	20.73	.228E+02	.411E+00
9.00	19.38	.204E+02	.352E+00	20.50	.215E+02	.360E+00
10.00	19.47	.194E+02	.310E+00	20.58	.206E+02	.337E+00
11.00	19.13	.183E+02	.282E+00	20.15	.194E+02	.296E+00
12.00	19.26	.183E+02	.267E+00	20.39	.194E+02	.303E+00
13.00	19.41	.177E+02	.265E+00	20.60	.188E+02	.275E+00
14.00	19.04	.167E+02	.260E+00	20.18	.177E+02	.253E+00
15.00	19.07	.160E+02	.235E+00	20.20	.170E+02	.255E+00
16.00	18.99	.157E+02	.212E+00	20.11	.168E+02	.253E+00
17.00	19.04	.149E+02	.204E+00	20.24	.160E+02	.255E+00
18.00	18.72	.140E+02	.199E+00	20.02	.161E+02	.247E+00
19.00	18.77	.141E+02	.202E+00	20.11	.152E+02	.228E+00
20.00	18.85	.143E+02	.190E+00	20.23	.154E+02	.215E+00
21.00	18.77	.134E+02	.186E+00	20.18	.145E+02	.210E+00
22.00	18.67	.134E+02	.182E+00	20.11	.145E+02	.206E+00
23.00	18.99	.128E+02	.152E+00	20.49	.138E+02	.172E+00
24.00	18.79	.129E+02	.140E+00	20.31	.140E+02	.158E+00
26.00	19.07	.123E+02	.141E+00	20.65	.133E+02	.159E+00
27.00	18.94	.123E+02	.138E+00	20.55	.134E+02	.151E+00
29.00	18.96	.118E+02	.103E+00	20.63	.129E+02	.121E+00
31.00	18.16	.968E+01	.901E-01	19.79	.107E+02	.108E+00
37.00	17.52	.858E+01	.769E-01	19.21	.951E+01	.957E-01
40.00	17.94	.848E+01	.668E-01	19.83	.944E+01	.843E-01
43.00	18.02	.774E+01	.496E-01	20.01	.867E+01	.667E-01
47.00	17.74	.739E+01	.334E-01	19.78	.836E+01	.548E-01
52.00	17.54	.662E+01	.264E-01	19.71	.760E+01	.504E-01

TABLE 4.21

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #132

N	AL	DKMAJL	DKMINL	DADNL	AR	DKMAJR	DKMINR	DADNR
49	.318	22.375	4.354	.02298	.326	22.733	4.424	.02782
54	.329	22.463	4.450	.02852	.333	22.640	4.485	.02852
65	.340	22.511	.4547	.03521	.348	22.859	4.617	.03464
70	.349	22.385	4.626	.03500	.359	22.814	4.715	.03387
78	.360	22.329	4.723	.02982	.364	22.497	4.759	.03479
86	.369	22.648	4.804	.03308	.375	22.902	4.858	.03426
94	.380	22.320	4.903	.03217	.386	22.568	4.957	.03274
100	.383	22.051	4.930	.03721	.396	22.582	5.049	.03780
108	.396	22.151	5.049	.04011	.406	22.557	5.141	.04345
115	.406	22.118	5.141	.04258	.417	22.562	5.244	.04856
121	.423	22.576	5.301	.05001	.428	22.779	5.349	.05318
124	.429	22.100	5.358	.04899	.440	22.539	5.465	.06441
128	.437	21.939	5.435	.05398	.451	22.493	5.573	.07620
132	.446	21.931	5.523	.04953	.463	22.603	5.693	.09271
136	.450	21.613	5.563	.04946	.477	22.673	5.836	.10294
139	.457	21.340	5.632	.05528	.489	22.586	5.961	.11654
141	.462	20.973	5.682	.05261	.501	22.477	6.090	.13789
143	.466	20.683	5.723	.06465	.517	22.646	6.266	.17087
145	.474	20.483	5.805	.10160	.529	22.592	6.402	.20602
146	.475	20.113	5.815	.12065	.539	22.547	6.519	.23495
147	.478	19.811	5.846	.15966	.551	22.578	6.663	.23586
148	.493	19.850	6.004	.13426	.562	22.476	6.798	.26489
149	.500	19.631	6.079	.11430	.575	22.487	6.963	.26988
150	.510	19.456	6.188	.10478	.582	22.180	7.055	.26353

TABLE 4.22

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #140

	-------LEFT CRACK---------			.--------RIGHT CRACK--------		
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
22.00	25.29	.213E+02	.508E+00	26.32	.222E+02	.551E+00
25.00	24.17	.187E+02	.415E+00	25.24	.195E+02	.418E+00
27.00	24.07	.158E+02	.350E+00	24.95	.164E+02	.345E+00
29.00	24.23	.147E+02	.290E+00	25.13	.152E+02	.289E+00
31.00	23.96	.134E+02	.252E+00	24.93	.139E+02	.254E+00
33.00	24.06	.121E+02	.238E+00	24.97	.125E+02	.222E+00
35.00	24.06	.117E+02	.206E+00	24.95	.121E+02	.201E+00
37.00	24.23	.110E+02	.179E+00	25.07	.114E+02	.180E+00
41.00	23.83	.992E+01	.126E+00	24.71	.103E+02	.143E+00

TABLE 4.23

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #141

	LEFT CRACK			RIGHT CRACK		
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
6.00	31.39	.254E+02	.642E+00	31.97	.260E+02	.706E+00
7.00	30.82	.230E+02	.582E+00	31.56	.237E+02	.612E+00
8.00	29.93	.213E+02	.526E+00	30.79	.219E+02	.546E+00
9.00	30.17	.202E+02	.510E+00	30.93	.207E+02	.510E+00
10.00	29.53	.184E+02	.450E+00	30.26	.189E+02	.462E+00
11.00	29.75	.177E+02	.420E+00	30.57	.182E+02	.447E+00
12.00	29.38	.169E+02	.388E+00	30.20	.173E+02	.398E+00
14.00	28.57	.149E+02	.333E+00	29.41	.153E+02	.340E+00
16.00	28.43	.138E+02	.286E+00	29.29	.143E+02	.295E+00
18.00	28.56	.128E+02	.247E+00	29.42	.132E+02	.260E+00
21.00	28.26	.106E+02	.196E+00	29.23	.110E+02	.212E+00
24.00	27.95	.101E+02	.162E+00	29.06	.105E+02	.176E+00
27.00	27.59	.915E+01	.143E+00	28.75	.956E+01	.145E+00
31.00	27.37	.863E+01	.123E+00	28.62	.900E+01	.117E+00
36.00	27.81	.758E+01	.101E+00	28.96	.786E+01	.938E-01
42.00	27.64	.618E+01	.781E-01	28.60	.641E+01	.766E-01
48.00	27.84	.834E+01	.553E-01	28.98	.557E+01	.652E-01
60.00	26.70	.450E+01	.367E-01	28.10	.476E+01	.471E-01
74.00	26.46	.329E+01	.310E-01	28.18	.353E+01	.370E-01
89.00	26.21	.258E+01	.304E-01	28.29	.280E+01	.324E-01
100.00	26.09	.120E+01	.325E-01	28.33	.130E+01	.315E-01

TABLE 4.24

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #142

	LEFT CRACK			RIGHT CRACK		
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
2.00	35.70	.251E+02	.730E+00	36.67	.256E+02	.670E+00
3.00	35.41	.230E+02	.660E+00	36.15	.235E+02	.620E+00
4.00	35.42	.213E+02	.610E+00	36.03	.216E+02	.570E+00
5.00	34.90	.198E+02	.480E+00	35.39	.202E+02	.510E+00
6.00	35.13	.184E+02	.460E+00	35.69	.187E+02	.430E+00
7.00	34.34	.167E+02	.436E+00	34.81	.169E+02	.397E+00
10.00	33.28	.135E+02	.268E+00	33.75	.138E+02	.291E+00
12.00	32.83	.126E+02	.233E+00	33.44	.128E+02	.243E+00
14.00	33.23	.111E+02	.201E+00	33.90	.113E+02	.196E+00
17.00	32.22	.911E+01	.167E+00	32.82	.927E+01	.160E+00
20.00	32.73	.943E+01	.134E+00	33.30	.959E+01	.141E+00
24.00	32.66	.803E+01	.115E+00	33.30	.821E+01	.115E+00
28.00	32.35	.682E+01	.106E+00	33.00	.694E+01	.991E-01
34.00	32.33	.523E+01	.665E-01	32.96	.534E+01	.725E-01
40.00	32.04	.493E+01	.620E-01	32.77	.505E+01	.635E-01
47.00	32.41	.413E+01	.716E-01	33.18	.423E+01	.510E-01
57.00	32.67	.264E+01	.867E-01	32.83	.261E+01	.953E-01
64.00	33.30	.143E+01	.126E+00	33.30	.145E+01	.100E+00

TABLE 4.25

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #143

	-------LEFT CRACK	---------	.	-------RIGHT CRACK	--------	
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
6.00	14.56	.254E+02	.329E+00	14.33	.250E+02	.315E+00
8.00	14.75	.238E+02	.273E+00	14.54	.235E+02	.284E+00
10.00	14.60	.222E+02	.246E+00	14.43	.219E+02	.263E+00
12.00	14.64	.210E+02	.222E+00	14.51	.208E+02	.233E+00
14.00	14.61	.199E+02	.217E+00	14.54	.198E+02	.214E+00
16.00	14.41	.189E+02	.205E+00	14.33	.187E+02	.189E+00
18.00	14.55	.191E+02	.182E+00	14.41	.188E+02	.154E+00
22.00	14.00	.162E+02	.129E+00	13.78	.159E+02	.115E+00
26.00	14.16	.152E+02	.955E-01	13.89	.149E+02	.956E-01
32.00	13.94	.140E+02	.755E-01	13.71	.138E+02	.859E-01
38.00	14.30	.134E+02	.627E-01	14.17	.133E+02	.708E-01
45.00	14.06	.123E+02	.497E-01	13.99	.122E+02	.528E-01

TABLE 4.26

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #144

	-------LEFT CRACK	---------	.	-------RIGHT CRACK	--------	
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
65.00	15.04	.106E+02	.441E-01	14.39	.101E+02	.373E-01
75.00	15.15	.108E+02	.419E-01	14.43	.102E+02	.447E-01
87.00	15.12	.101E+02	.320E-01	14.44	.967E+01	.377E-01
118.00	14.55	.951E+01	.333E-01	13.61	.864E+01	.128E-01
147.00	14.90	.954E+01	.301E-01	13.09	.809E+01	.116E-01

TABLE 4.27

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #145

	-------LEFT CRACK---------			-------RIGHT CRACK--------		
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
15.00	20.29	.167E+02	.104E+00	19.70	.163E+02	.104E+00
19.00	19.96	.164E+02	.113E+00	19.45	.160E+02	.113E+00
23.00	19.63	.156E+02	.108E+00	19.15	.153E+02	.112E+00
27.00	19.75	.151E+02	.107E+00	19.32	.148E+02	.108E+00
31.00	19.71	.145E+02	.101E+00	19.32	.142E+02	.995E-01
36.00	19.71	.140E+02	.875E-01	19.33	.137E+02	.904E-01
41.00	19.25	.132E+02	.768E-01	18.91	.130E+02	.837E-01
47.00	19.42	.135E+02	.736E-01	19.15	.134E+02	.770E-01
53.00	19.44	.129E+02	.727E-01	19.20	.127E+02	.728E-01
59.00	19.37	.123E+02	.632E-01	19.14	.121E+02	.650E-01
67.00	19.13	.109E+02	.534E-01	18.92	.108E+02	.587E-01
74.00	19.18	.110E+02	.553E-01	19.04	.109E+02	.615E-01
81.00	19.28	.106E+02	.505E-01	19.20	.106E+02	.565E-01
90.00	19.02	.993E+01	.434E-01	19.00	.994E+01	.504E-01
100.00	19.08	.954E+01	.417E-01	19.15	.960E+01	.476E-01
110.00	19.03	.912E+01	.350E-01	19.18	.920E+01	.397E-01
126.00	18.69	.810E+01	.225E-01	18.93	.823E+01	.284E-01
145.00	18.57	.777E+01	.203E-01	18.94	.796E+01	.257E-01
165.00	18.57	.684E+01	.179E-01	19.09	.706E+01	.226E-01
190.00	18.33	.624E+01	.148E-01	18.99	.649E+01	.187E-01
217.00	18.38	.601E+01	.128E-01	19.18	.630E+01	.162E-01
252.00	18.31	.556E+01	.924E-02	19.26	.587E+01	.119E-01

TABLE 4.28

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #146

	-------LEFT CRACK	---------	.	--------RIGHT CRACK	--------	
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
29.00	19.25	.144E+02	.312E-01	18.33	.137E+02	.305E-01
47.00	19.23	.137E+02	.284E-01	18.34	.131E+02	.290E-01
62.00	19.41	.131E+02	.235E-01	18.56	.126E+02	.240E-01
89.00	19.01	.121E+02	.150E-01	18.21	.116E+02	.153E-01
115.00	18.83	.115E+02	.144E-01	18.08	.110E+02	.146E-01
145.00	18.55	.108E+02	.134E-01	17.83	.104E+02	.137E-01
175.00	18.45	.102E+02	.124E-01	17.76	.982E+01	.126E-01
211.00	18.29	.956E+01	.113E-01	17.62	.922E+01	.115E-01
250.00	18.11	.871E+01	.102E-01	17.47	.840E+01	.104E-01
293.00	18.12	.830E+01	.927E-02	17.49	.801E+01	.945E-02
354.00	18.06	.826E+01	.798E-02	17.45	.799E+01	.814E-02
412.00	18.10	.761E+01	.691E-02	17.50	.736E+01	.705E-02
472.00	18.20	.690E+01	.620E-02	17.61	.668E+01	.632E-02
543.00	18.13	.653E+01	.553E-02	17.55	.632E+01	.564E-02
626.00	18.14	.614E+01	.484E-02	17.58	.595E+01	.493E-02
713.00	18.31	.631E+01	.412E-02	17.75	.612E+01	.421E-02
823.00	18.26	.567E+01	.338E-02	17.71	.549E+01	.345E-02
961.00	18.40	.519E+01	.296E-02	17.84	.504E+01	.302E-02
1143.00	18.97	.585E+01	.235E-02	18.40	.568E+01	.238E-02
1390.00	19.21	.488E+01	.143E-02	18.63	.473E+01	.142E-02
1769.00	19.15	.480E+01	.934E-03	18.55	.465E+01	.927E-03
2371.00	19.02	.471E+01	.585E-03	18.41	.456E+01	.581E-03

TABLE 4.29

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #147

	-------LEFT CRACK	---------	.	--------RIGHT CRACK	--------	
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
7.00	24.48	.162E+02	.128E+00	25.19	.167E+02	.125E+00
11.00	24.50	.154E+02	.119E+00	25.15	.158E+02	.120E+00
17.00	24.31	.153E+02	.120E+00	24.91	.157E+02	.122E+00
24.00	24.46	.142E+02	.112E+00	25.04	.145E+02	.113E+00
28.00	24.74	.137E+02	.117E+00	25.30	.140E+02	.119E+00
32.00	24.72	.134E+02	.111E+00	25.27	.137E+02	.113E+00
40.00	24.16	.122E+02	.810E-01	24.72	.125E+02	.855E-01
45.00	24.38	.117E+02	.807E-01	24.99	.119E+01	.852E-01
50.00	24.40	.111E+02	.764E-01	25.05	.114E+02	.790E-01
56.00	24.24	.107E+02	.662E-01	24.89	.110E+02	.680E-01
62.00	23.92	.102E+02	.667E-01	24.57	.105E+02	.683E-01
68.00	24.09	.970E+01	.574E-01	24.76	.997E+01	.595E-01
80.00	23.75	.900E+01	.359E-01	24.47	.930E+01	.428E-01
91.00	23.45	.873E+01	.349E-01	24.30	.907E+01	.417E-01
103.00	23.55	.793E+01	.335E-01	24.53	.828E+01	.399E-01
115.00	23.26	.723E+01	.303E-01	24.36	.759E+01	.362E-01
129.00	23.47	.687E+01	.290E-01	24.72	.726E+01	.346E-01
142.00	23.48	.648E+01	.268E-01	24.88	.688E+01	.319E-01
160.00	22.87	.588E+01	.223E-01	24.38	.628E+01	.266E-01
178.00	23.34	.584E+01	.211E-01	25.04	.628E+01	.251E-01
198.00	23.32	.517E+01	.174E-01	25.18	.560E+01	.219E-01
274.00	21.97	.382E+01	.506E-02	24.31	.432E+01	.107E-01

TABLE 4.30

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #148

	-------LEFT CRACK---------			.-------RIGHT CRACK--------		
N	DKMAJOR	DKMINOR	DADN	DKMAJOR	DKMINOR	DADN
7.00	29.70	.162E+02	.125E+00	29.80	.163E+02	.138E+00
10.00	30.63	.164E+02	.140E+00	30.87	.166E+02	.160E+00
13.00	30.89	.162E+02	.134E+00	31.30	.164E+02	.138E+00
17.00	30.53	.153E+02	.125E+00	30.89	.155E+02	.105E+00
21.00	30.85	.151E+02	.120E+00	30.97	.151E+02	.110E+00
25.00	31.05	.145E+02	.108E+00	31.05	.145E+02	.111E+00
29.00	30.70	.138E+02	.104E+00	30.73	.138E+02	.108E+00
33.00	30.76	.133E+02	.100E+00	30.83	.134E+02	.981E-01
39.00	30.28	.128E+02	.942E-01	30.29	.128E+02	.889E-01
44.00	30.52	.123E+02	.855E-01	30.46	.122E+02	.876E-01
49.00	30.49	.122E+02	.780E-01	30.45	.122E+02	.842E-01
55.00	30.29	.112E+02	.678E-01	30.33	.112E+02	.735E-01
62.00	30.08	.104E+02	.583E-01	30.19	.105E+02	.637E-01
69.00	29.89	.975E+01	.556E-01	30.09	.983E+01	.611E-01
77.00	30.03	.954E+01	.505E-01	30.31	.964E+01	.560E-01
85.00	29.95	.910E+01	.462E-01	30.32	.923E+01	.458E-01
96.00	29.89	.852E+01	.438E-01	30.21	.858E+01	.398E-01
105.00	29.98	.820E+01	.417E-01	30.20	.826E+01	.423E-01
118.00	30.11	.792E+01	.343E-01	30.36	.800E+01	.349E-01
132.00	29.64	.736E+01	.273E-01	29.90	.742E+01	.281E-01
148.00	29.79	.697E+01	.236E-01	30.09	.705E+01	.266E-01
167.00	29.83	.633E+01	.210E-01	30.25	.644E+01	.207E-01
195.00	29.64	.550E+01	.163E-01	29.98	.554E+01	.147E-01
231.00	29.42	.523E+01	.106E-01	29.71	.530E+01	.126E-01
275.00	29.00	.423E+01	.915E-02	29.47	.431E+01	.109E-01
320.00	28.83	.388E+01	.899E-02	29.50	.398E+01	.107E-01
362.00	28.35	.325E+01	.918E-02	29.20	.336E+01	.110E-01
404.00	28.44	.285E+01	.925E-02	29.49	.296E+01	.110E-01
447.00	28.39	.241E+01	.935E-02	29.67	.253E+01	.112E-01
489.00	28.07	.140E+01	.986E-02	29.59	.148E+01	.118E-01
531.00	27.98	.145E+01	.104E-01	29.77	.156E+01	.124E-01
568.00	27.91	.121E+01	.127E-01	30.02	.131E+01	.151E-01

TABLE 4.31

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #149

N	LEFT CRACK DKMAJOR	LEFT CRACK DKMINOR	LEFT CRACK DADN	RIGHT CRACK DKMAJOR	RIGHT CRACK DKMINOR	RIGHT CRACK DADN
2.00	27.82	.170E+02	.106E+01	29.62	.179E+02	.929E+00
3.00	26.77	.150E+02	.940E+00	28.06	.157E+02	.870E+00
4.00	26.37	.136E+02	.797E+00	27.43	.140E+02	.771E+00
5.00	25.89	.122E+02	.590E+00	26.84	.126E+02	.640E+00
6.00	25.20	.111E+02	.517E+00	26.20	.116E+02	.583E+0[illegible]
8.00	24.45	.960E+01	.386E+00	25.55	.101E+02	.406E+00
10.00	23.98	.847E+01	.399E+00	25.12	.888E+01	.334E+00
12.00	24.59	.771E+01	.364E+00	25.53	.793E+01	.301E+00
16.00	24.45	.711E+01	.150E+00	25.42	.747E+01	.207E+00

TABLE 4.32

MAJOR/MINOR CRACK GROWTH RATE DATA
FOR TEST #150

N	LEFT CRACK DKMAJOR	LEFT CRACK DKMINOR	LEFT CRACK DADN	RIGHT CRACK DKMAJOR	RIGHT CRACK DKMINOR	RIGHT CRACK DADN
2.00	25.60	.135E+02	.740E+00	26.09	.137E+02	.770E+00
3.00	24.94	.122E+02	.609E+00	25.46	.125E+02	.695E+00
4.00	24.60	.112E+02	.530E+00	25.27	.115E+02	.560E+00
5.00	24.05	.102E+02	.467E+00	24.75	.105E+02	.467E+00
7.00	23.15	.870E+01	.380E+00	23.74	.889E+01	.365E+00
9.00	23.87	.818E+01	.371E+00	24.44	.840E+01	.355E+00
11.00	23.41	.719E+01	.315E+00	23.92	.732E+01	.270E+00
13.00	23.50	.617E+01	.342E+00	23.86	.626E+01	.347E+00
14.00	24.02	.658E+01	.323E+00	24.37	.668E+01	.342E+00
16.00	24.07	.609E+01	.186E+00	24.46	.619E+01	.197E+00
19.00	23.60	.492E+01	.189E+00	24.04	.502E+01	.200E+00
21.00	23.72	.434E+01	.205E+00	24.24	.444E+01	.218E+00
23.00	23.55	.374E+01	.224E+00	24.12	.383E+01	.238E+00
25.00	23.63	.362E+00	.228E+00	24.28	.373E+01	.242E+00
27.00	23.65	.349E+01	.238E+00	24.39	.360E+01	.253E+00
29.00	23.94	.337E+01	.280E+00	24.78	.350E+01	.297E+00
31.00	24.00	.236E+01	.347E+00	24.98	.246E+01	.368E+00
33.00	24.53	.190E+01	.475E+00	25.73	.200E+01	.504E+00
34.00	25.43	.132E+01	.499E+00	26.91	.140E+01	.529E+00
35.00	26.12	.103E+01	.494E+00	27.88	.110E+01	.525E+00

SECTION 5

MODEL FOR THE ESTIMATION OF MAJOR/MINOR CYCLE DAMAGE

It is apparent from the major/minor cycle test data shown in Section 4 that the high frequency minor cycle loading may increase the fatigue crack propagation rate. The most obvious point is the "threshold" value for ΔK_{minor}, below which the minor cycle has no effect. This section will describe the various mechanisms that contribute to the major/minor cycle behavior.

The two principal regimes of crack propagation in Inconel-718 under major/minor cycle loading at elevated temperatures are fatigue and creep. Each of these regimes may consist of one or more individual mechanisms. Some of the mechanisms that dominate the crack propagation are well understood and analyzed, others are not.

The major/minor cycle loading consists of a minor load cycle superimposed onto the major load cycle. The major cycle and the minor cycle make their own contributions to creep and to fatigue. For this reason, the modeling of major/minor cycle behavior is best broken down into four components:

1. Major cycle fatigue
2. Minor cycle fatigue
3. Major cycle creep
4. Minor cycle creep.

The fatigue due to both major and minor cycles will be treated as linear elastic for the purposes of this report.

A Paris-type law will be used to describe the crack p[illegible]-gation rate per major cycle due to fatigue.

$$\frac{da}{dM}(\text{major cycle fatigue}) = C\,\frac{(\Delta K_{major}-\Delta K_o)^Q}{(1-R_{major})}\left(\frac{MM}{\text{Major Cycl}}\right.$$

and

$$\frac{da}{dM}(\text{minor cycle fatigue}) = C\,\frac{(\Delta K_{minor}-\Delta K_o)^Q}{(1-R_{major})}\left(\frac{MM}{\text{Major C}}\right.$$

where

$C \cong 7.3 \times 10$

$Q \cong 1.46$

and

$\Delta K_o = 15\ (1-R)^{0.6}$

where R is either R_{major} or R_{minor}.

If either ΔK_{major} or ΔK_{minor} is less than the corresp[illegible] ΔK_o then that mechanism does not produce any crack growth, [illegible], $da/dM = 0$).

The creep propagation rate is given by a general (non-constitutive) equation

$$\frac{da}{dM}(\text{major cycle creep}) = A(HT)\left(\frac{(\Delta K_{major})}{(1-R_{major})}\right)^P\left(\frac{MM}{\text{Major Cycle}}\right)$$

where

$A = 1.29 \times 10^{-15}$

HT = Hold Time (Sec)

$P = 7.28$.

The effect of the minor cycle on creep is not taken into account because it would be small compared to the major cycle contribution for values of $\Delta K_{minor} < \Delta K_o$, the threshold for fatigue.

It has yet to be demonstrated that stress intensity factor is useful for correlating creep crack growth rate data. The ligament stress, i.e., the stress in the unfractured portion of the specimen, may be expected to have better correlating qualities for creep crack growth.

A comparison was made of stress intensity factor (K) and the ligament stress for a center cracked panel under constant K conditions. The study indicated that for most of the test, meaning for most crack lengths, a constant K test resulted in nominally constant ligament stress. Figure 5.1 demonstrates the range the range of crack length in which the ligament stress is nominally constant. Based on this result, the constant ΔK_{major} tests were run for crack lengths that maintained constant ligament stress. In this manner, it is not critical whether the stress intensity factor or the ligament stress is used for presenting the major/minor cycle data. The stress intensity factor was used in this report to maintain consistency with the fatigue results. The constants used for the crack growth rate equations were determined from the data generated during this program and reported in Section 4.

A linear summation model has been developed that uses these rate equations to estimate the crack propagation rate due to the major/minor cycle loading.

The key element of the linear summation model is that crack propagation is due to either creep or fatigue, but not both. This occurs because creep and fatigue are competing mechanisms.

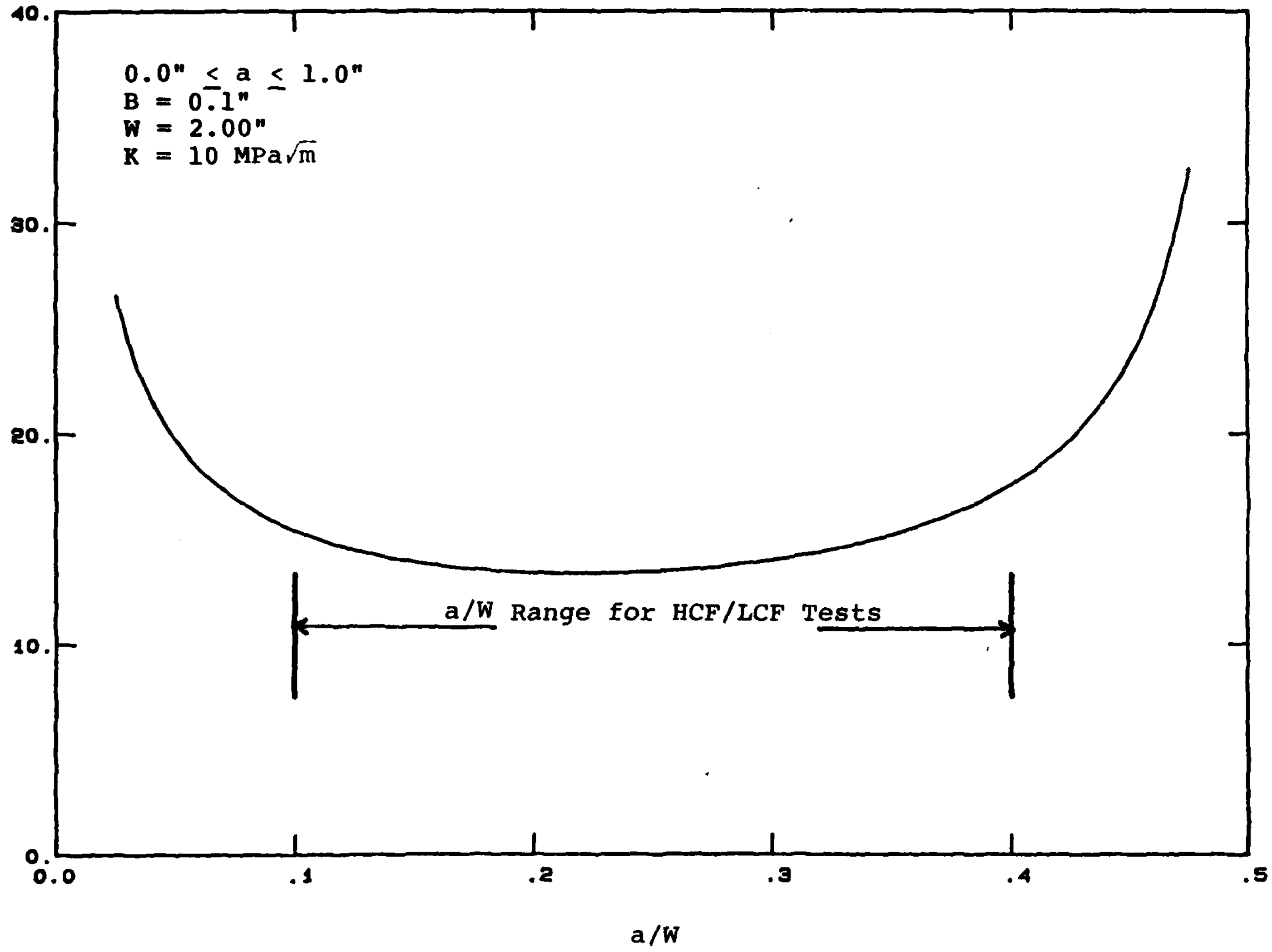

Figure 5.1. Ligament Tensile Stress Under Constant K.

If the creep rate is fast enough, the crack tip will be blunted and crack propagation will be due to creep crack growth rather than fatigue.

For this reason, crack propagation is due either to fatigue or creep.

the linear summation law developed to estimate major/minor cycle damage is:

$$\frac{da}{dM}\left(\frac{mm}{cycle}\right) = (\text{major cycle creep rate})$$

OR

[(major cycle fatigue rate)+(minor cycle fatigue rate)]

whichever is larger.

Figure 5.2 is a major/minor cycle fatigue map that shows the crack propagation rate contours due to various values of ΔK_{major}. The two competing mechanisms are evident from the break in slopes, i.e., the creep regime results in a flat valley in which ΔK_{minor} has no effect.

The fatigue regime occurs at higher values of ΔK_{minor} and the crack growth rate increases with ΔK_{minor}. The contours in the fatigue regime are due to the stress ratio (R_{minor}) effect on crack growth rate.

The two crack growth mechanism regimes are labeled on the fatigue map.

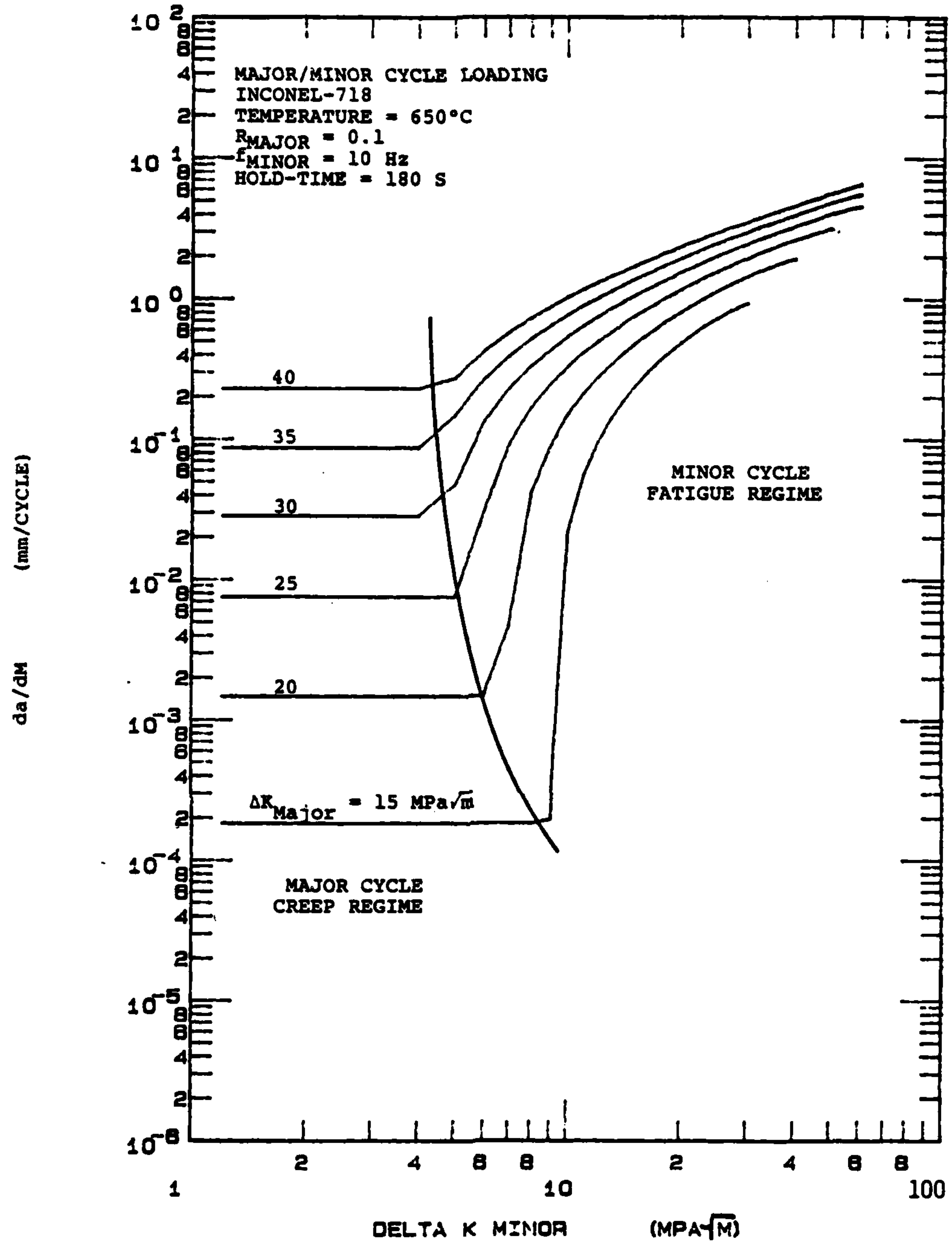

Figure 5.2. Crack Growth Rate as a Function of ΔK_{Minor} for Various ΔK_{Major}.

SECTION 6
CONCLUSIONS

The major/minor cycle experiments, conducted as part of this program, indicate that the superimposed minor cycle loading does have an effect on the crack propagation behavior of the major cycle. The minor cycle has a threshold stress intensity factor range, ΔK_o, associated with it. For values of ΔK_{minor} less than the threshold, no effect on the crack propagation behavior of the major cycle is apparent. For values of ΔK_{minor} above the threshold, the crack propagation rate increases rapidly. The influence of the minor cycle loading appears to be proportional to its frequency, doubling the minor cycle frequency doubles its influence on the crack propagation rate of the major cycle.

It is evident, from the experimental data, that the ΔK_o value is stress ratio dependent. As the minor cycle stress ratio, R_{minor} increases, the threshold value decreases. At high levels of ΔK_{major}, the minor cycle amplitude has greater influence than at lower values of ΔK_{major}.

The experiments also indicate that there are at least two regimes of crack propagation mechanism fatigue and creep. At high levels of ΔK_{minor} the fatigue mechanism(s) is dominant. The fatigue regime is characterized by sharp fatigue cracks and cycle dependent crack propagation.

At lower levels of ΔK_{minor} the creep mechanism(s) is dominant. The creep regime is characterized by plastic deformation around the crack resulting in a blunted crack tip and time dependent crack propagation.

A non-constitutive linear summation model has been developed that permits the effect of ΔK_{major} and ΔK_{minor} on the crack propagation rate to be evaluated.

The linear summation model also predicts the effects of stress ratio, hold-time, and minor cycle frequency on the crack growth rate. The model accounts for fatigue crack growth, as well as creep crack growth in Inconel-718 at 650°C.

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APPENDIX I

CONSTANT LOAD AMPLITUDE TESTS

This appendix contains data generated during the first year of the program. During this period, a number of constant load amplitude tests were run on sheet Inconel-718 at 650°C. The data is presented as da/dM vs ΔK_{major} plots and in tabular form. These tests are included in the test matrix given in Section 2 as Table 2.1.

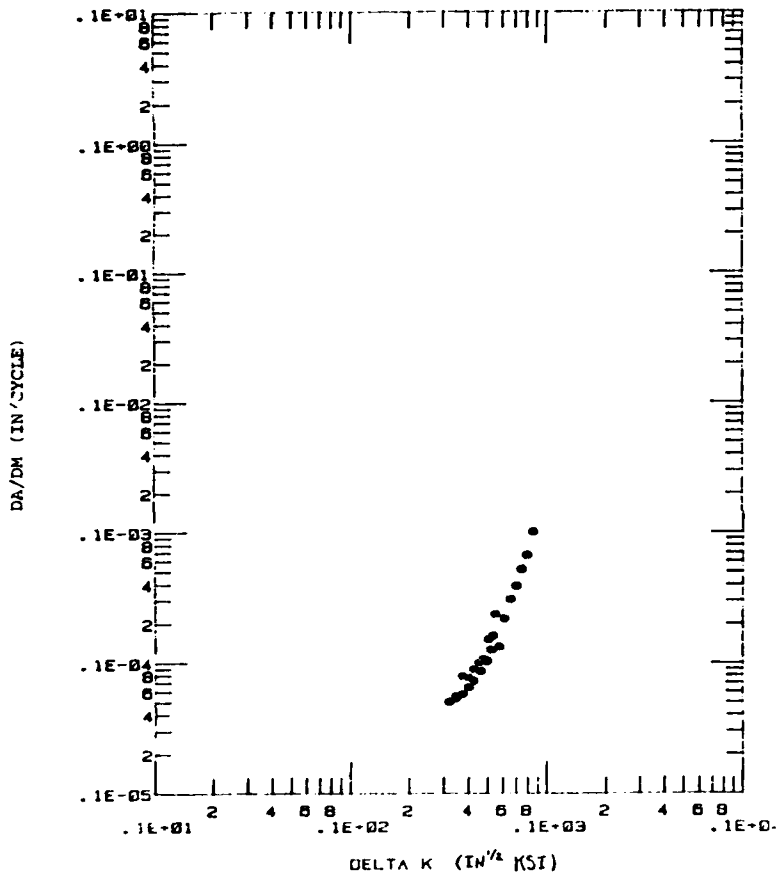

Figure A1.1. Test #2.

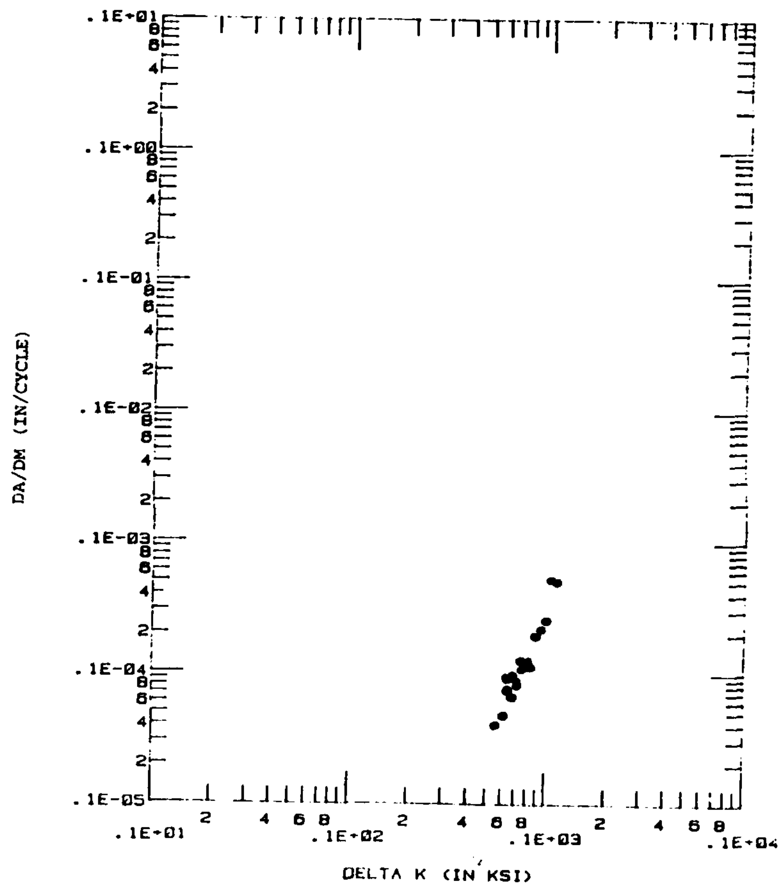

Figure A1.2. Test #3.

AD-A124 585 HIGH FREQUENCY FATIGUE OF TURBINE BLADE MATERIAL(U)
DAYTON UNIV OH RESEARCH INST R C GOODMAN ET AL. OCT 82
UDR-TR-82-104 AFWAL-TR-82-4151 F33615-79-C-5108

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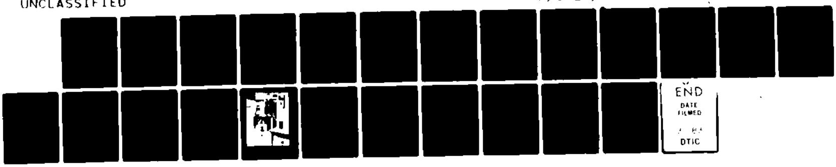

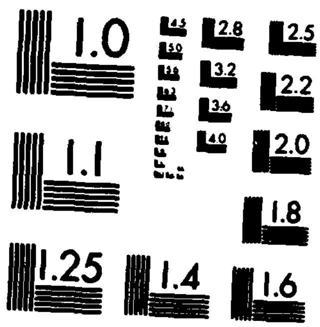

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Figure A1.3. Test #4.

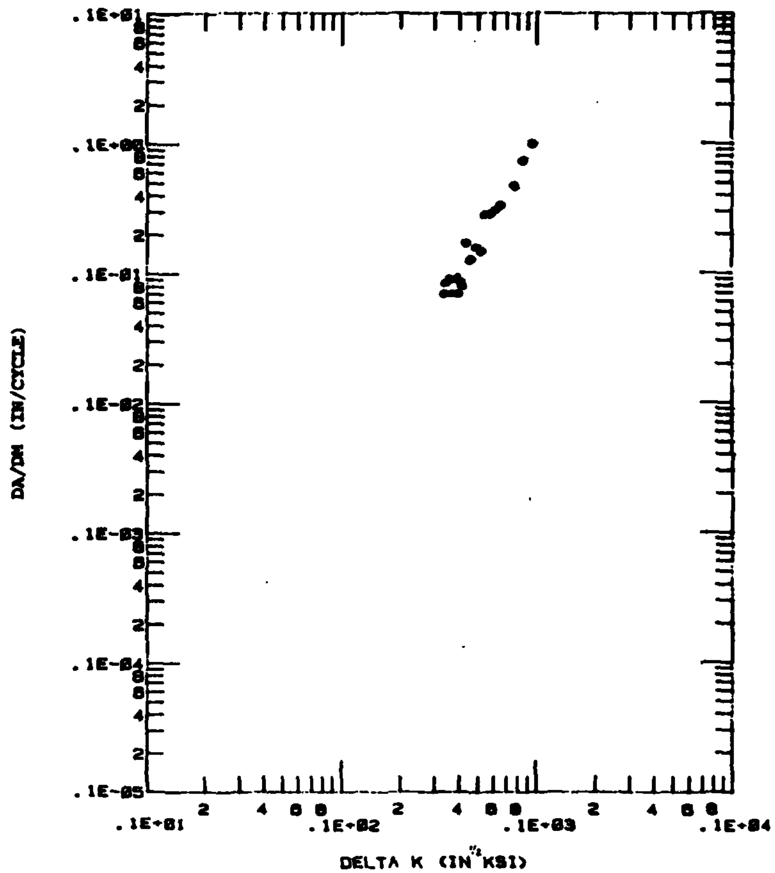

Figure A1.4. Test #5.

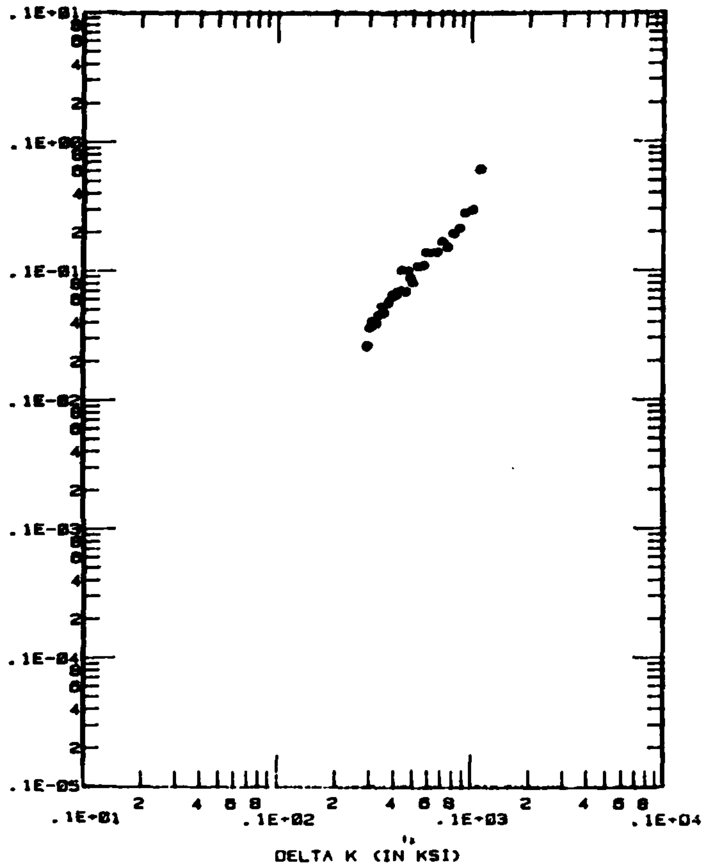

Figure A1.5. Test #6.

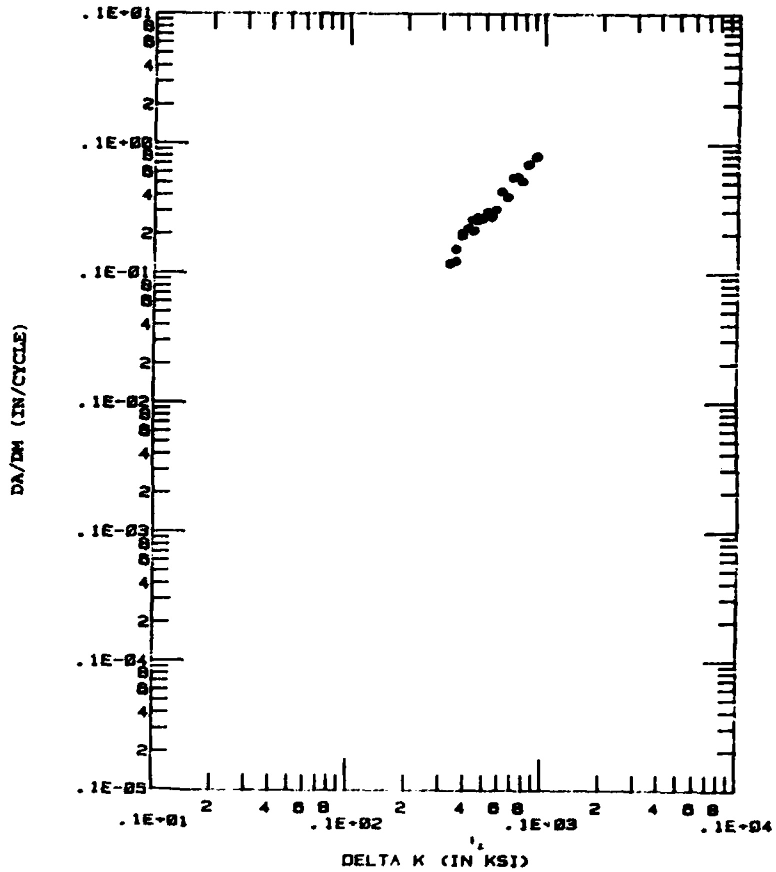

Figure A1.6. Test #7.

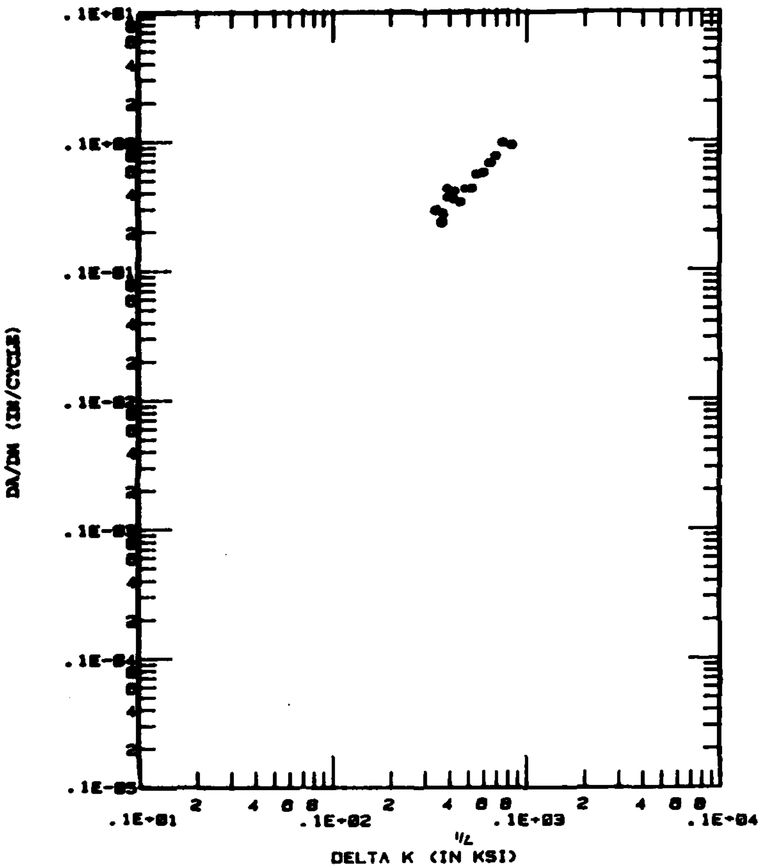

Figure A1.7. Test #8.

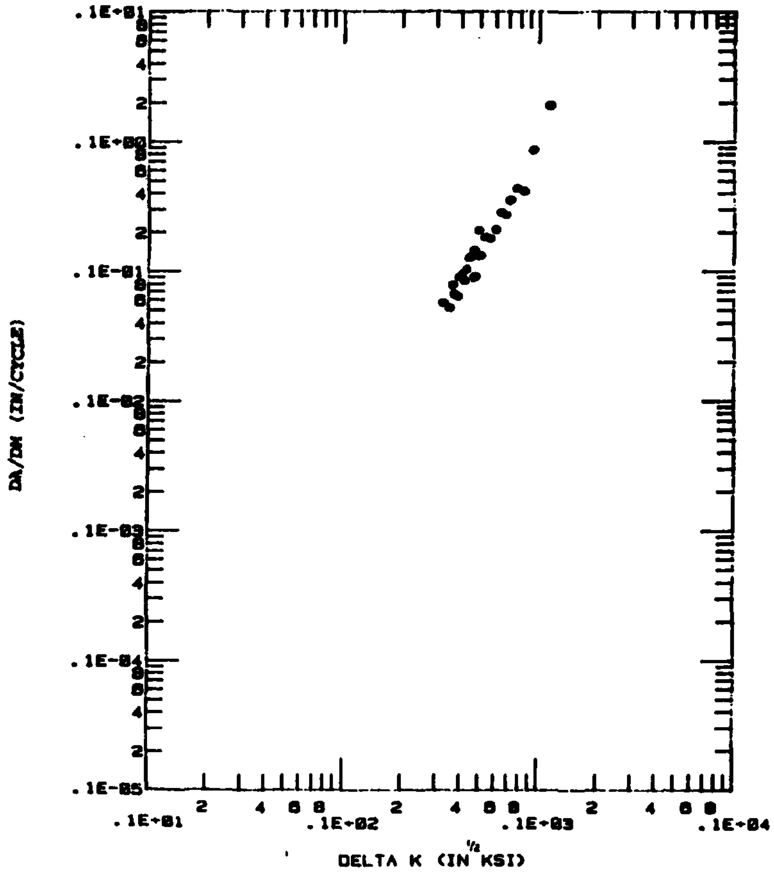

Figure A1.8. Test #9.

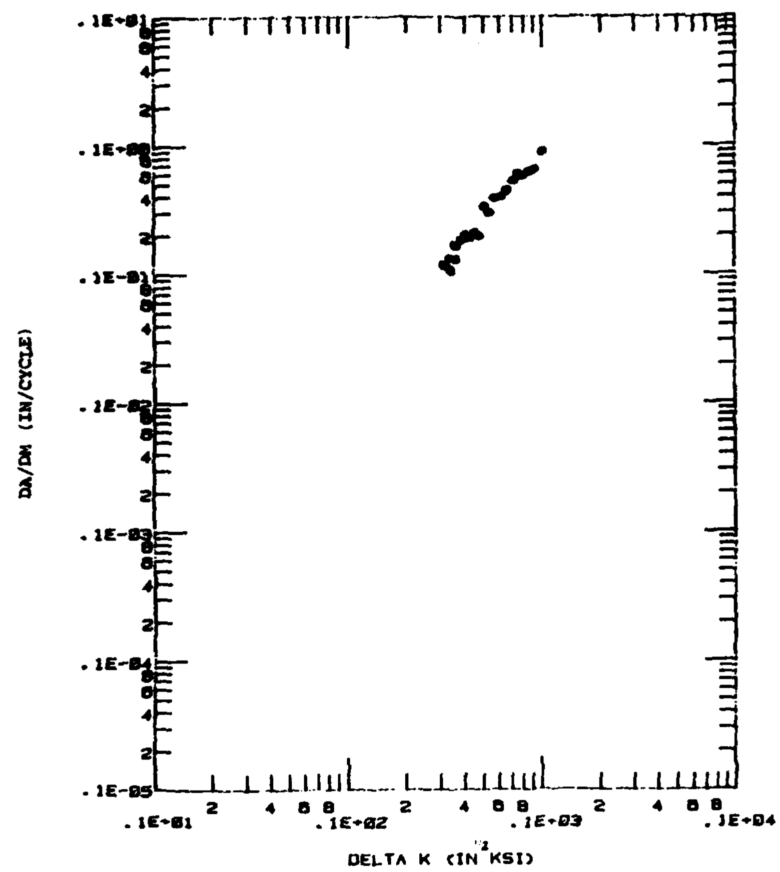

Figure A1.9. Test #10.

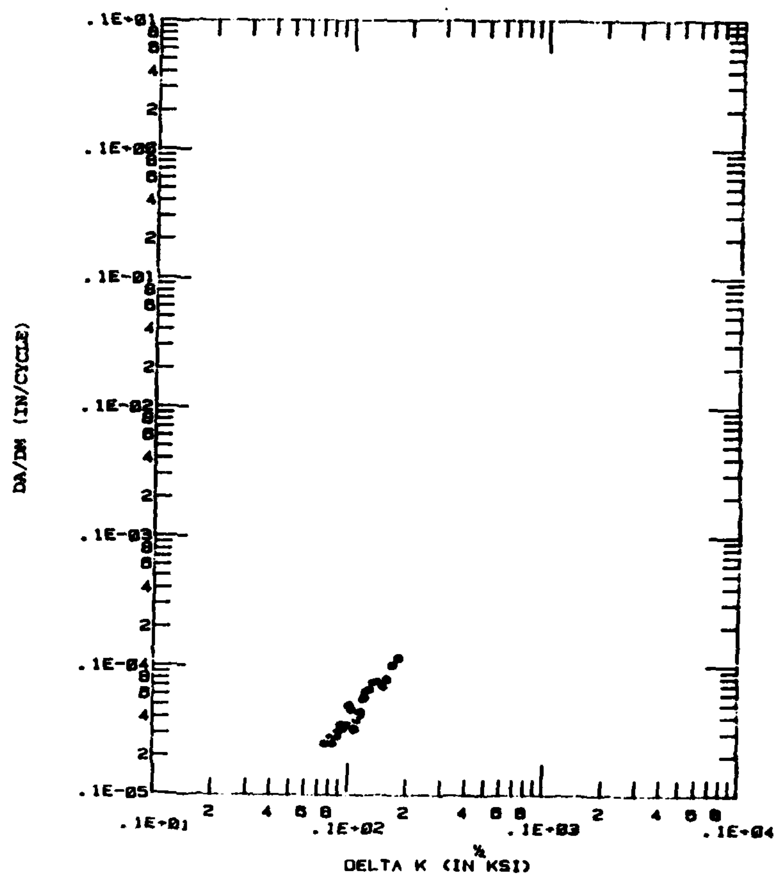

Figure A1.10. Test #11.

TABLE A1.1

CRACK PROPAGATION DATA FOR TEST NO. 2

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
11550.	.4555	32.1	35.7	.525E-05
23300.	.5210	34.7	38.6	.582E-05
34040.	.5935	37.6	41.7	.829E-05
42561.	.6630	40.3	44.8	.803E-05
50031.	.7270	42.9	47.6	.937E-05
56026.	.7870	45.3	50.3	.106E-04
62031.	.8530	48.1	53.4	.113E-04
67032.	.9190	51.0	56.7	.160E-04
70544.	.9765	53.7	59.6	.169E-04

RIGHT CRACK PROPAGATION DATA

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
11550.	.5245	34.9	38.8	.564E-05
23300.	.5935	37.6	41.7	.604E-05
34040.	.6615	40.2	44.7	.681E-05
42561.	.7230	42.7	47.4	.759E-05
53037.	.8110	46.3	51.4	.901E-05
62031.	.8975	50.0	55.6	.108E-04
67032.	.9565	52.7	58.6	.132E-04
70036.	1.008	55.2	61.3	.250E-04
73034.	1.061	57.9	64.3	.140E-04
76532.	1.124	61.3	68.1	.230E-04
79233.	1.197	65.7	73.0	.326E-04
81178.	1.267	70.3	78.1	.408E-04
82426.	1.325	74.6	82.9	.550E-04
83325.	1.380	79.2	88.0	.702E-04
84025.	1.440	84.8	94.2	.106E-03

LEFT CRACK PROPAGATION DATA

The INCONEL 718 specimen was subjected to High Amplitude, Low Frequency (major) cycles with superimposed Low Amplitude, High Frequency (minor) cycles.

Thickness = 0.093"

Width = 4.000"

Hold-Time (Major) = 0.0 Min.

Minor Cycle Amp. = 0 Kip

Max Load (Major) = 10.75 Kip

Load Ratio (R) = 0.10

Frequency = 10 Hz

TABLE A1.2

CRACK PROPAGATION DATA FOR TEST NO. 3

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
45250.	.8030	63.8	128.	.909E-05
52500.	.8580	67.1	134.	.667E-05
61000.	.9205	70.9	142.	.812E-05
68000.	.9855	75.2	150.	.108E-04
73000.	1.043	79.1	158.	.125E-04
77500.	1.096	83.0	166.	.112E-04
81500.	1.153	87.5	175.	.193E-04
84500.	1.215	92.8	186.	.217E-04
87000.	1.272	98.2	196.	.250E-04
88550.	1.326	104.	207.	.518E-04
89700.	1.384	110.	221.	.500E-04

RIGHT CRACK PROPAGATION DATA

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
16000.	.6505	55.3	111.	.403E-05
38300.	.7450	60.5	121.	.476E-05
48800.	.8060	64.0	128.	.738E-05
56000.	.8660	67.6	135.	.967E-05
62000.	.9210	71.0	142.	.867E-05
67000.	.9720	74.3	149.	.125E-04

LEFT CRACK PROPAGATION DATA

The INCONEL 718 specimen was subjected to High Amplitude, Low Frequency (major) cycles with superimposed Low Amplitude, High Frequency (minor) cycles.

Thickness = 0.093"
Width = 4.000"
Hold-Time (Major) = 0 Min.
Minor Cycle Amp. = 0 Kip

Max Load (Major) = 10.75 Kip
Load Ratio (R) = 0.5
Frequency = 10 Hz

TABLE A1.3

CRACK PROPAGATION DATA FOR TEST NO. 4

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
2063.	.5005	31.9	35.4	.252E-02
2084.	.5610	34.1	37.9	.322E-02
2102.	.6175	36.2	40.2	.306E-02
2119.	.6700	38.1	42.4	.313E-02
2133.	.7275	40.3	44.7	.542E-02
2147.	.8035	43.2	48.0	.580E-02
2159.	.8815	46.3	51.5	.690E-02
2167.	.9420	48.9	54.3	.104E-01

RIGHT CRACK PROPAGATION DATA

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
2060.	.5260	32.8	36.5	.290E-02
2077.	.5840	34.9	38.8	.414E-02
2093.	.6460	37.2	41.4	.388E-02
2106.	.7065	39.5	43.9	.550E-02
2119.	.7645	41.7	46.3	.381E-02
2132.	.8260	44.1	49.0	.689E-02
2140.	.8830	46.4	51.6	.743E-02
2146.	.9345	48.6	54.0	.850E-02
2157.	1.024	52.6	58.4	.847E-02
2168.	1.162	59.7	66.3	.188E-01
2175.	1.280	66.9	74.3	.170E-01
2179.	1.361	72.8	80.9	.257E-01
2182.	1.437	79.3	88.1	.250E-01
2185.	1.510	86.8	96.5	.240E-01

LEFT CRACK PROPAGATION DATA

The INCONEL 718 specimen was subjected to High Amplitude, Low Frequency (major) cycles with superimposed Low Amplitude, High Frequency (minor) cycles.

Thickness = 0.093"

Width = 4.000"

Hold-Time (Major) = 3 Min.

Minor Cycle Amp. = 0.0 Kip

Max Load (Major) = 10.75 Kip

Load Ratio (R) = 0.10

Frequency (Minor) = 0 Hz

TABLE A1.4

CRACK PROPAGATION DATA FOR TEST NO. 5

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
5.	.5095	32.9	36.5	.811E-02
13.	.5730	35.3	39.2	.675E-02
21.	.6270	37.3	41.4	.675E-02
29.	.6855	39.5	43.9	.787E-02

RIGHT CRACK PROPAGATION DATA

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
11.	.5115	32.9	36.6	.700E-02
18.	.5700	35.1	39.0	.900E-02
24.	.6240	37.2	41.3	.900E-02
31.	.6860	39.5	43.9	.875E-02
37.	.7555	42.2	46.9	.173E-01
41.	.8155	44.6	49.5	.128E-01
46.	.8810	47.3	52.5	.160E-01
50.	.9510	50.3	55.9	.150E-01
53.	1.010	53.0	58.9	.285E-01
55.	1.067	55.8	62.0	.290E-01
57.	1.127	59.0	65.5	.310E-01
59.	1.192	62.6	69.6	.335E-01
62.	1.364	74.5	82.8	.475E-01
64.	1.449	82.1	91.2	.750E-01
65.	1.536	91.8	102.	.100

LEFT CRACK PROPAGATION DATA

The INCONEL 718 specimen was subjected to High Amplitude, Low Frequency (major) cycles with superimposed Low amplitude, High Frequency (minor) cycles.

Thickness = 0.093"

Width = 4.000'

Hold-Time (Major) = 10 Min.

Minor Cycle Amp. = 0.0 Kip

Max Load (Major) = 10.75 Kip

Load Ratio (R) = 0.10

Frequency (Minor) = 0 Hz

TABLE A1.5

CRACK PROPAGATION DATA FOR TEST NO. 6

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
10.	.4040	28.5	31.7	.250E-02
27.	.4540	30.4	33.8	.385E-02
40.	.5070	32.4	36.0	.431E-02
52.	.5620	34.5	38.3	.450E-02
63.	.6145	36.4	40.5	.567E-02
72.	.6680	38.4	42.7	.622E-02
81.	.7240	40.5	45.1	.622E-02
88.	.7810	42.8	47.5	.967E-02
95.	.8365	45.0	50.0	.663E-02
102.	.8885	47.1	52.3	.850E-02

RIGHT CRACK PROPAGATION DATA

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
8.	.4270	29.4	32.7	.350E-02
23.	.4815	31.5	35.0	.370E-02
37.	.5410	33.7	37.5	.508E-02
49.	.6060	36.1	40.1	.533E-02
60.	.6650	38.3	42.6	.600E-02
69.	.7220	40.5	45.0	.667E-02
78.	.7825	42.8	47.6	.678E-02
87.	.8560	45.8	50.8	.956E-02
95.	.9300	48.9	54.3	.775E-02
102.	.9920	51.7	57.4	.103E-01
108.	1.055	54.6	60.7	.105E-01
113.	1.113	57.6	64.0	.133E-01
118.	1.179	61.2	68.0	.132E-01
123.	1.245	65.3	72.5	.133E-01
127.	1.303	69.2	76.9	.160E-01
131.	1.364	73.8	82.0	.145E-01
135.	1.421	78.7	87.4	.187E-01
138.	1.480	84.4	93.8	.207E-01
140.	1.538	91.1	101.	.270E-01
142.	1.594	98.6	110.	.285E-01
144.	1.651	108.	120.	.580E-01

LEFT CRACK PROPAGATION DATA

The INCONEL 718 specimen was subjected to High Amplitude, Low Frequency (major) cycles with superimposed Low Amplitude, High Frequency (minor) cycles.

Thickness = 0.093"
Width = 4.000"
Hold-Time = 3 Min
Minor Cycle Amp = 2.15 Kip

Max Load = 10.75 Kip
Load Ratio (R) = 0.10
HCF Frequency = 10 Hz

TABLE A1.6

CRACK PROPAGATION DATA FOR TEST NO. 7

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
3.	.4510	32.0	35.5	.116E-01
7.	.5095	34.3	38.1	.148E-01
11.	.5765	36.9	41.0	.188E-01
15.	.6465	39.7	44.1	.217E-01
18.	.7095	42.1	46.8	.203E-01
20.	.7665	44.5	49.4	.265E-01
22.	.8185	46.6	51.8	.255E-01
25.	.8845	49.5	55.0	.270E-01

RIGHT CRACK PROPAGATION DATA

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
3.	.4545	32.1	35.7	.118E-01
8.	.5150	34.5	38.3	.124E-01
12.	.5770	36.9	41.0	.207E-01
15.	.6415	39.5	43.8	.223E-01
17.	.7010	41.8	46.5	.260E-01
19.	.7525	43.9	48.8	.255E-01
22.	.8195	46.7	51.8	.277E-01
24.	.8910	49.8	55.3	.300E-01
26.	.9485	52.4	58.2	.275E-01
28.	1.008	55.2	61.3	.315E-01
30.	1.082	59.0	65.6	.430E-01
32.	1.164	63.7	70.7	.390E-01
34.	1.231	67.8	75.4	.550E-01
35.	1.286	71.7	79.6	.560E-01
36.	1.340	75.8	84.2	.520E-01
37.	1.401	81.0	90.9	.700E-01
38.	1.476	88.5	98.4	.800E-01

LEFT CRACK PROPAGATION DATA

The INCONEL 718 specimen was subjected to High Amplitude, Low Frequency (major) cycles with superimposed Low Amplitude, High Frequency (minor) cycles.

Thickness = 0.093"
Width = 4.000"
Hold-Time = 10 Min.
Minor Cycle Amp. = 2.15 Kip

Max Load = 10.75 Kip
Load Ratio (R) = 0.10
HCF Frequency = 10 Hz

TABLE A1.7

CRACK PROPAGATION DATA FOR TEST NO. 8

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
9.	.4920	32.9	36.5	.280E-01
11.	.5605	35.5	39.5	.265E-01
13.	.6220	37.9	42.1	.350E-01
15.	.6910	40.5	45.0	.340E-01
17.	.7520	42.9	47.7	.540E-01

RIGHT CRACK PROPAGATION DATA

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
9.	.4880	32.7	36.4	.520E-01
11.	.5480	35.0	38.9	.227E-01
13.	.6230	37.9	42.1	.410E-01
15.	.7035	41.0	45.6	.395E-01
17.	.7755	43.9	48.8	.325E-01
19.	.8490	46.9	52.1	.410E-01
21.	.9315	50.5	56.1	.415E-01
23.	.9995	53.6	59.6	.530E-01
26.	1.168	62.5	69.5	.650E-01
27.	1.237	66.8	74.3	.740E-01
28.	1.321	72.7	80.8	.940E-01
29.	1.413	80.4	89.4	.900E-01

LEFT CRACK PROPAGATION DATA

The INCONEL 718 specimen was subjected to High Amplitude, Low Frequency (major) cycles with superimposed Low Amplitude, High Frequency (minor) cycles.

Thickness = 0.093"

Width = 4.000"

Hold-Time (Major) = 10 Min.

Minor Cycle Amp. = 2.15 Kip

Max Load (Major) = 10.75 Kip

Load Ratio (R) = 0.10

Frequency (Minor) = 40 Hz

TABLE A1.8

CRACK PROPAGATION DATA FOR TEST NO. 9

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
9.	.5340	35.2	39.2	.771E-02
16.	.5860	37.3	41.4	.625E-02
23.	.6390	39.4	43.7	.933E-02
29.	.6920	41.4	46.1	.100E-01
33.	.7420	43.5	48.3	.125E-01
39.	.7985	45.8	50.9	.900E-02
45.	.8625	48.5	53.9	.130E-01
49.	.9220	51.1	56.8	.180E-01
52.	.9840	54.0	60.0	.175E-01
56.	1.060	57.9	64.3	.205E-01
59.	1.129	61.6	68.5	.280E-01
61.	1.184	64.8	72.0	.265E-01
63.	1.245	68.8	76.4	.345E-01
65.	1.322	74.3	82.6	.425E-01
67.	1.405	81.4	90.4	.405E-01
69.	1.487	89.8	99.7	.840E-01
70.	1.623	109.	121.	.187

RIGHT CRACK PROPAGATION DATA

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
6.	.4395	31.5	35.0	.555E-02
17.	.4980	33.8	37.6	.509E-02
26.	.5520	36.0	39.9	.650E-02
33.	.6045	38.0	42.2	.883E-02
40.	.6600	40.2	44.6	.829E-02
46.	.7200	42.6	47.3	.124E-01
50.	.7790	45.0	50.0	.140E-01
54.	.8370	47.4	52.7	.200E-01

LEFT CRACK PROPAGATION DATA

The INCONEL 718 specimen was subjected to High Amplitude, Low Frequency (major) cycles with superimposed Low Amplitude, High Frequency (minor) cycles.

Thickness = 0.093"

Width = 4.000"

Hold-Time (Major) = 10 Min

Minor Cycle Amp. = 0.0 Kip

Max Load (Major) = 10.75 Kip

Load Ratio (R) = 0.10

Frequency (Minor) = 0 Hz

TABLE A1.9

CRACK PROPAGATION DATA FOR TEST NO. 10

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
3.	.4130	30.4	33.8	.112E-01
7.	.4665	32.6	36.2	.128E-01
11.	.5245	34.9	38.8	.163E-01
15.	.5840	37.2	41.3	.180E-01
18.	.6405	39.4	43.8	.197E-01
21.	.6980	41.7	46.3	.187E-01
24.	.7565	44.0	48.9	.203E-01
27.	.8160	46.5	51.7	.193E-01
29.	.8775	49.2	54.6	.325E-01
31.	.9395	51.9	65.7	.390E-01
33.	1.007	55.2	61.3	.380E-01
35.	1.084	59.1	65.7	.390E-01
37.	1.167	63.8	70.9	.435E-01
39.	1.236	68.2	75.8	.520E-01
40.	1.292	72.1	80.1	.590E-01
41.	1.350	76.6	85.1	.570E-01
42.	1.409	81.7	90.8	.610E-01
43.	1.471	88.0	97.8	.640E-01
44.	1.547	97.1	108.	.870E-01

RIGHT CRACK PROPAGATION DATA

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
3.	.4135	30.4	33.8	.114E-01
8.	.4680	32.6	36.3	.104E-01
12.	.5195	34.7	38.5	.128E-01
16.	.5800	37.0	41.2	.175E-01
20.	.6425	39.5	43.9	.183E-01

LEFT CRACK PROPAGATION DATA

The INCONEL 718 specimen was subjected to High Amplitude, Low Frequency (major) cycles with superimposed Low amplitude, High Frequency (minor) cycles.

Thickness = 0.093"

Width = 4.000"

Hold-Time (Major) = 10 Min.

Minor Load Amp. = 2.15 Kip

Max Load (Major) = 10.75 Kip

Load Ratio (R) = 0.10

Frequency (Minor) = 10 Hz

TABLE A1.10

CRACK PROPAGATION DATA FOR TEST NO. 11

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
28730.	.5530	7.91	44.0	.244E-05
50775.	.6100	8.40	46.7	.274E-05
71345.	.6670	8.90	49.4	.280E-05
89815.	.7240	9.40	52.2	.342E-05
106295.	.7805	9.90	55.0	.344E-05
120320.	.8370	10.4	57.9	.482E-05
136360.	.8980	11.0	61.2	.319E-05
154400.	.9625	11.7	64.8	.405E-05
168500.	1.029	12.4	68.7	.551E-05

RIGHT CRACK PROPAGATION DATA

CYCLES	A(IN)	DELTAK	KMAX	DA/DN
69300.	.6200	8.49	47.2	.249E-05
91835.	.6815	9.02	50.1	.300E-05
112320.	.7450	9.58	53.2	.320E-05
130370.	.8045	10.1	56.2	.341E-05
145940.	.8655	10.7	59.4	.446E-05
160965.	.9270	11.3	62.8	.373E-05
174525.	.9810	11.9	65.8	.430E-05
185285.	1.036	12.5	69.2	.615E-05
194000.	1.091	13.1	72.7	.638E-05
202000.	1.145	13.8	76.4	.725E-05
210000.	1.204	14.5	80.7	.737E-05
218000.	1.260	15.4	85.3	.675E-05
225500.	1.314	16.2	90.1	.771E-05
232000.	1.371	17.2	95.8	.100E-04
238000.	1.435	18.5	103.	.112E-04

LEFT CRACK PROPAGATION DATA

The INCONEL 718 specimen was subjected to High Amplitude, Low Frequency (major) cycles with superimposed Low Amplitude, High Frequency (minor) cycles.

Thickness = 0.093"

Width = 4.000"

Hold-Time (Major) = 0 Min

Minor Cycle Amp. = 0 Kip

Max Load (Major) = 10.75 Kip

Load Ratio (R) = 0.82

Frequency = 10 Hz

APPENDIX II

S-N DATA FOR INCONEL-718

During the early stages of this program, several fatigue life tests, (S-N tests), were run on Inconel-718 hourglass specimens. The tests were conducted in laboratory air at 650°C. Figure A2.1 shows the cycles to failure curve obtained from these tests.

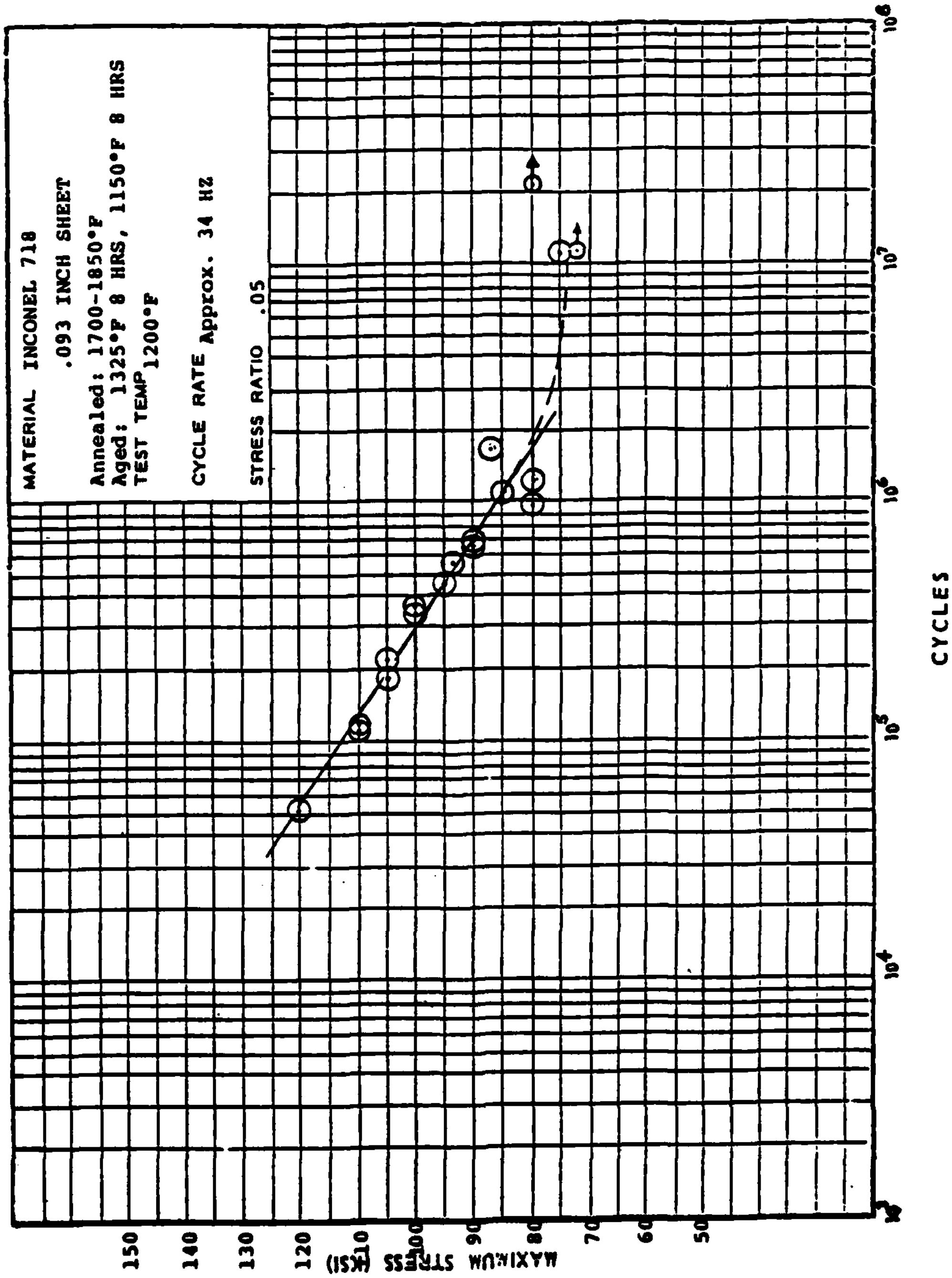

Figure A2.1. S-N Curve for IN 718.

APPENDIX III

A3.1 EXPLANATION OF APPARATUS

The technique investigated involves mechanically coupling a standard electromagnetic shaker to a hydraulic cylinder which is in turn hydraulically plumbed to the specimen loading cylinder. The apparatus is pictured in Figure A3.1 and illustrated schematically in Figure A3.2. Shaker excitation of cylinder A is hydraulically transferred to cylinder B (the specimen loading cylinder) and is superimposed on any preload existing in cylinder B. Centering of the shaker armature is not affected by the preload pressure. Operation of the experimental system is as follows: with valve V1 open, the specimen (load cell in this case) is preloaded by hand-pump generated pressure. Since valve V1 is open while establishing the preload, the pressure is equal on both sides of double acting cylinder A; thus, the shaker armature remains centered. After preloading pressure is established, valve V1 may be closed and shaker operation started. Displacement of the upper part of cylinder A causes proportional displacement of loading cylinder B. The load cell is connected to an oscilloscope by which the dynamic load may be observed and measured. Displacement of the lower section of cylinder A is accomodated by the accumulator. Overtravel of the shaker armature is prevented by mechanical stops on cylinder A.

Test Results

Tabulated in Table A3.1 is the experimental test data. Figures A3.3 to A3.8 are photographs of oscilloscope traces taken at various conditions during the experiment.

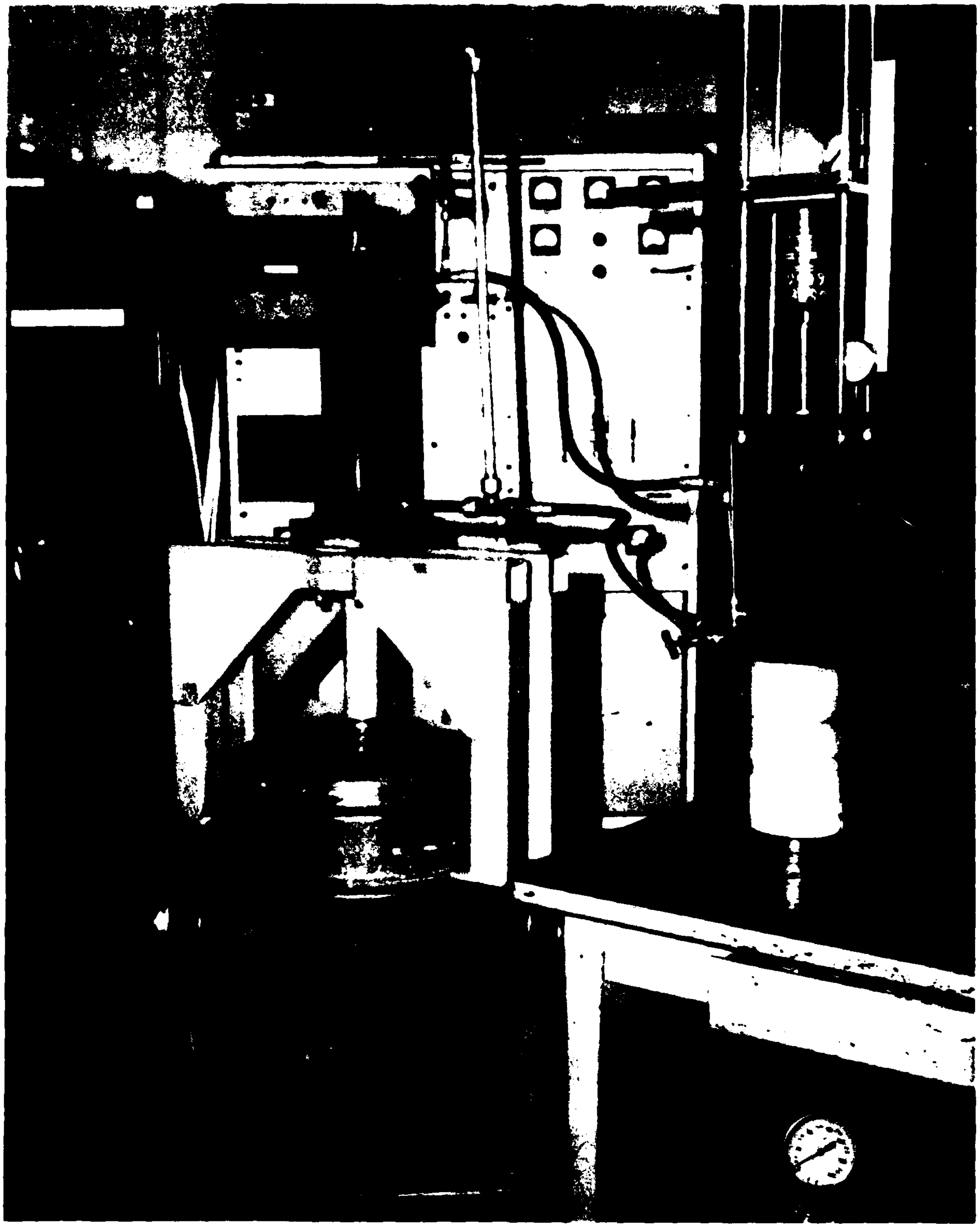

Figure A3.1. Electromagnetic Shaker/Hydraulic Ram HCF/LCF Unit.

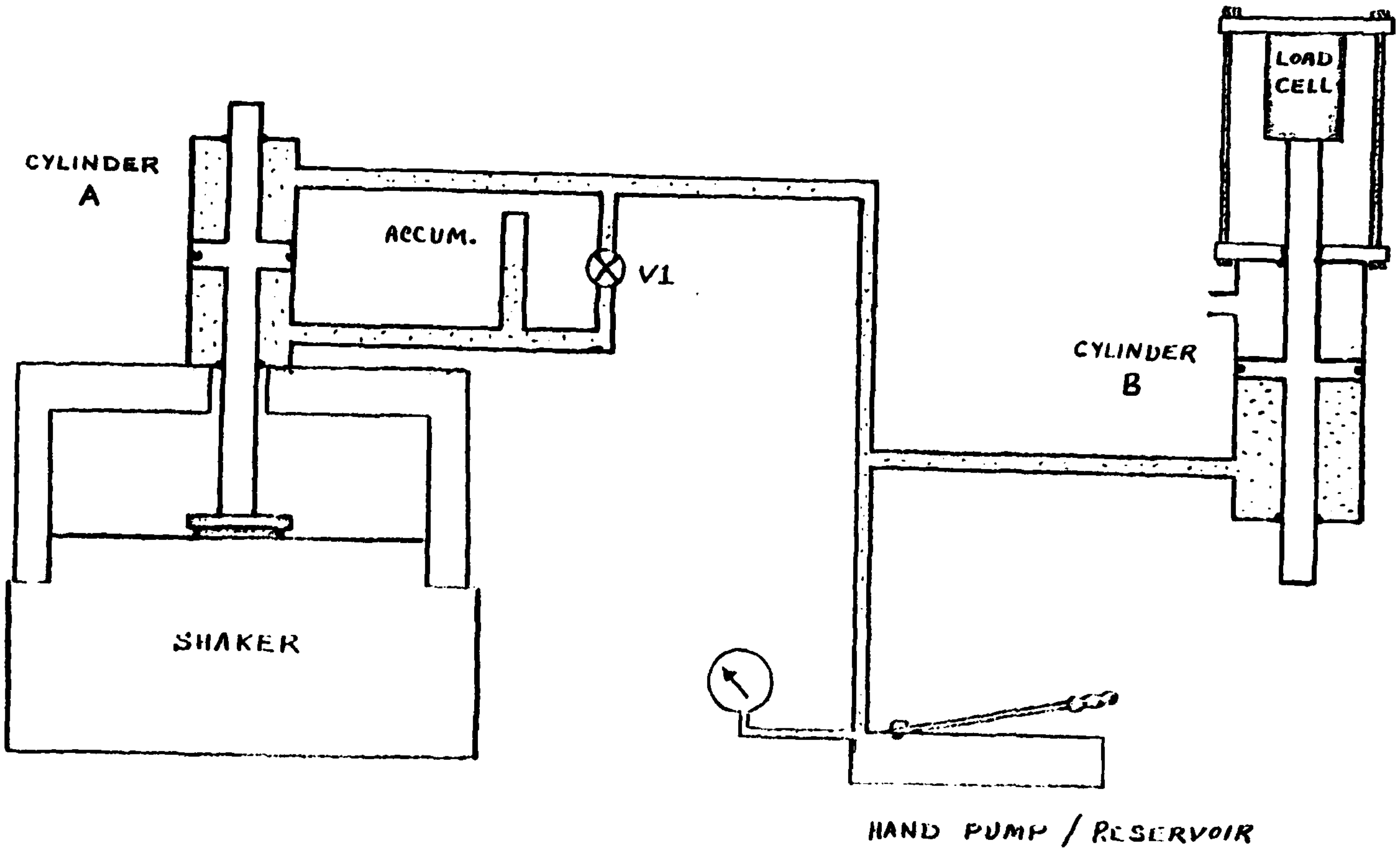

Figure A3.2. Diagram of Electromagnetic Shaker/Hydraulic Ram HCF/LCF Unit.

TABLE A3.1

TEST DATA

330 psig preload pressure 3110 lb. preload; amplifier current held at 15 amps; fixture stiffness 210 Kip/inch

f Hz	Load Cell Volts	Dynamic Load lb. p-p	Percent of preload
20	0.4	248	8
30	0.8	497	16
40	0.86	534	17
55	0.43	267	8.6
60	0.36	224	7.2
70	0.35	217	7.0
75	0.44	273	8.8
100	0.40	248	8.0
105	0.40	248	8.0
110	0.35	217	7.0
115	0.23	143	4.6
120	0.19	118	3.8
122	0.15	93	3.0
125	0.125	78	2.5
150	0.05	31	10
175	0.025	16	5
200	0.015	9	0.3

430 psig preload pressure; 4050 lb. preload; same amplifier power as above; fixture stiffness 274 Kip/inch

f Hz	Load Cell Volts	Dynamic Load lb. p-p	Percent of preload
40	0.5	310	7.7
50	0.33	205	5.1
60	0.22	137	3.4
70	0.32	200	4.9
80	0.27	168	4.1
90	0.34	210	5.2
100	0.6	373	9.2
110	0.4	248	6.1
120	0.2	124	3.1
130	0.12	75	1.8
150	0.07	43	1.1

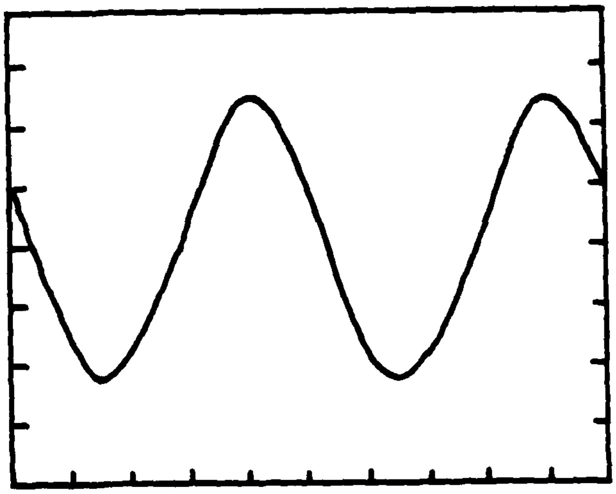

Figure A3.3. Load Cell Output 0.553 KN/Division, 40 Hz.

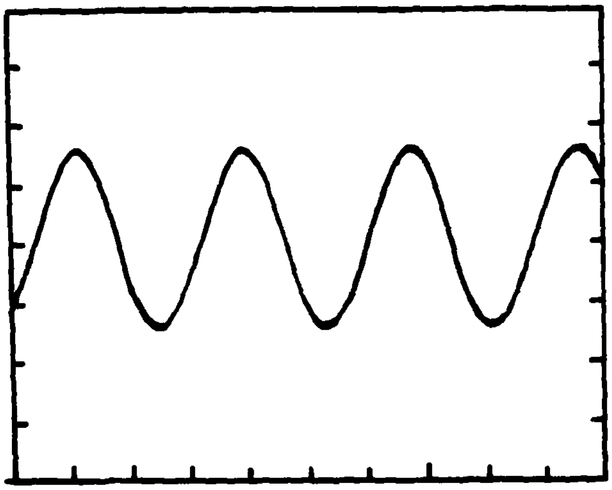

Figure A3.4. Load Cell Output 0.276 KN/Division, 70 Hz.

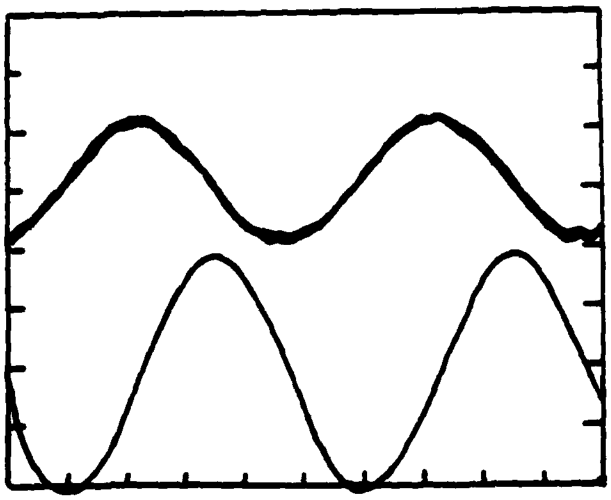

Figure A3.5. Load Cell Output vs Drive Signal 0.276 KN/ Division, 0.1 V/Division, 100 Hz.

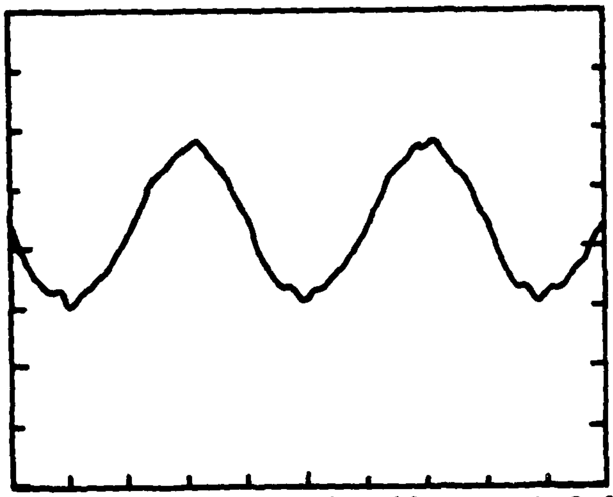

Figure A3.6. Load Cell Output 0.138 KN/Division, 125 Hz.

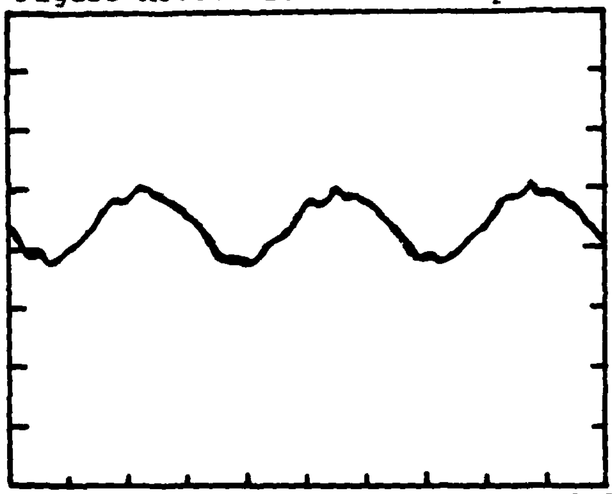

Figure A3.7. Load Cell Output 0.138 KN/Division, 150 Hz.

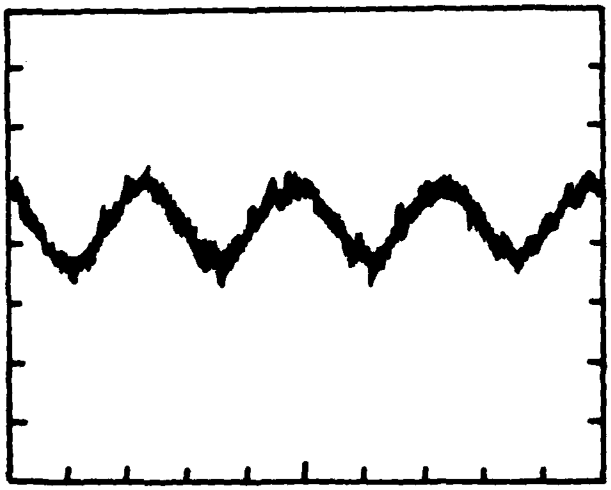

Figure A3.8. Load Cell Output 0.0553 KN/Division, 200 Hz.

A3.2 EQUIPMENT IDENTIFICATION

1. Electromagnetic shaker: MB model/C10E, S/N 636, 1200 lb. maximum force

2. Cylinder A: Parker Hannifin KJB-2HS 24/29, bore 3.2 inch, 2 inch diameter shaft

3. Cylinder B: MTS model 202.25, piston area 9.42 inches^2

4. Accumulator: standpipe 27 inches high x 3/4 inch diameter

5. Load cell: Baldwin SR4

6. Pressure gage: specially calibrated by dead weight tester.

A3.3 LOAD CELL CALIBRATION

A static pressure of 330 psig was applied to the system and 5.0 volts was measured on the scope.

$$330 \text{ psig} \times 9.42 \text{ in}^2 = 3109 \text{ lb. load}$$

$$\frac{5.0 \text{ volts}}{3100 \text{ lbs.}} = 0.00161 \text{ volts/lb.}$$

A3.4 CALIBRATION CHECK OF PRESSURE GAGE BY DEAD WEIGHT TESTER

Dead Weight (psig)	Pressure Gage (psig)
100	180
200	270
300	375
400	470
500	570
600	670

A3.5 STIFFNESS OF TEST FIXTURE

The stiffness of the B cylinder fixture was determined by measuring fixture deflection under various static loads. A dial indicator provided the deflection measurement, while the pressure gage provided the data to compute load.

Pressure	Corrected Pressure	Load	Deflection	Stiffness (lb/in)
300 psig	230 psig	2170	0(REF.)	---
400	330	3110	0.005	188,000
500	430	4050	0.004	236,000
600	530	4995	0.003	314,000

The fixture was then modified by insertion of rubber "isomode" pad between fixture and load cell and results were as follows:

Corrected Pressure	Load	Deflection	Stiffness
230 psig	2170	0(Ref.)	---
330	3110	.0058	162,000
430	4050	.0049	192,000
530	4995	.0033	285,000

*USGPO:1983-639-062-725

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